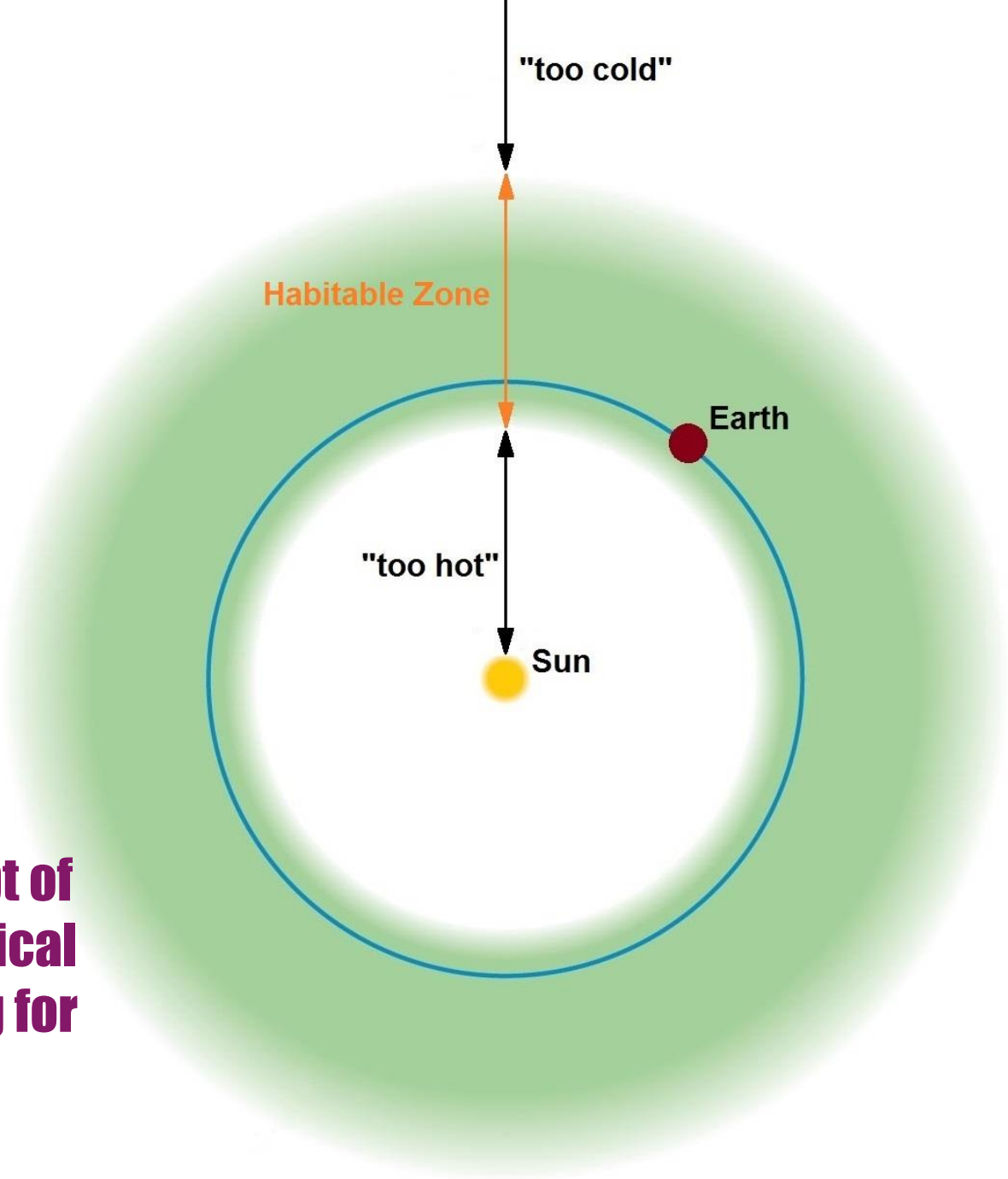
Astronomy Winter School Hyderabad 2017

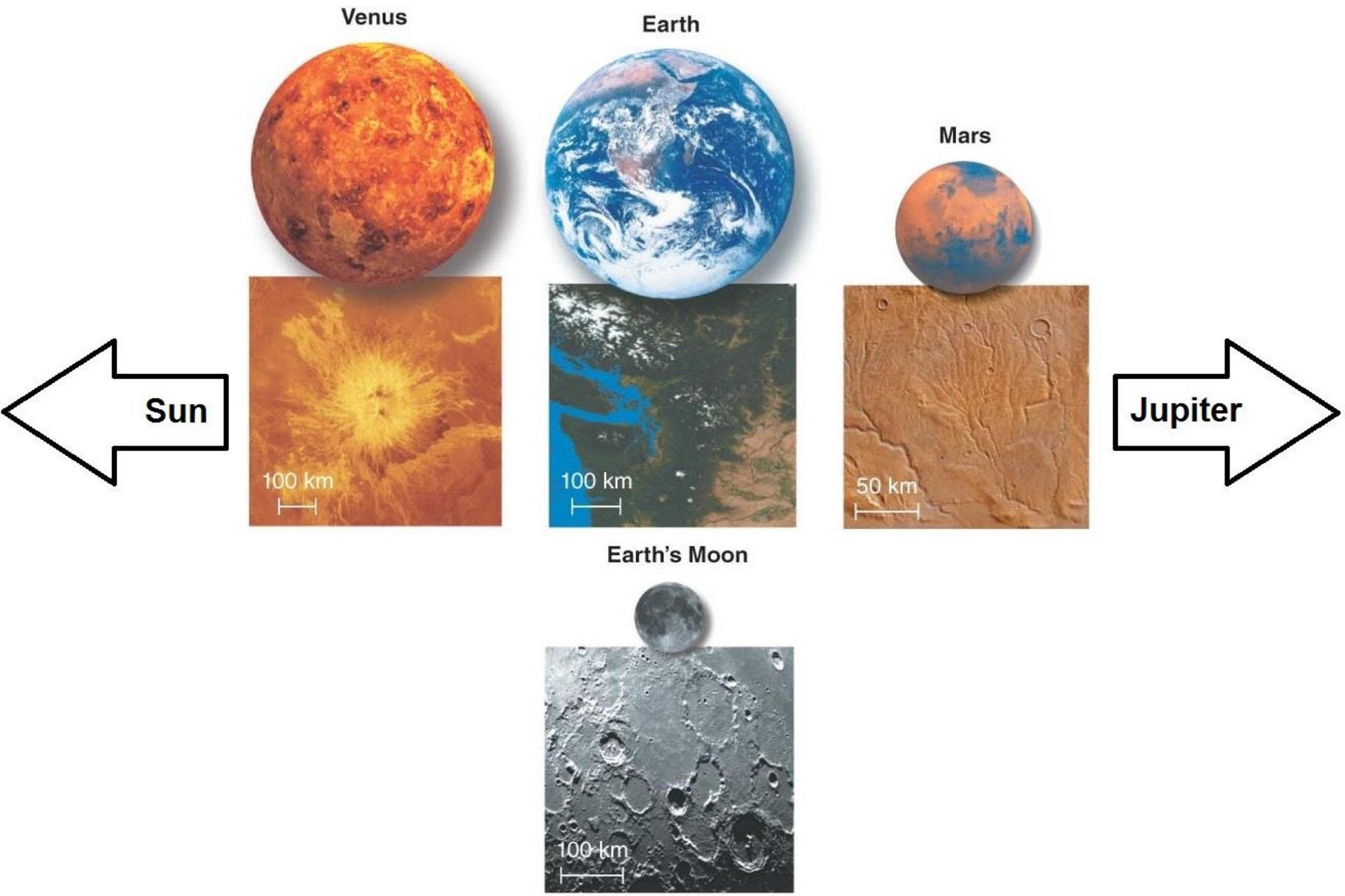
Supplement
Habitability and Exoplanets

Current approach in Astrobiology

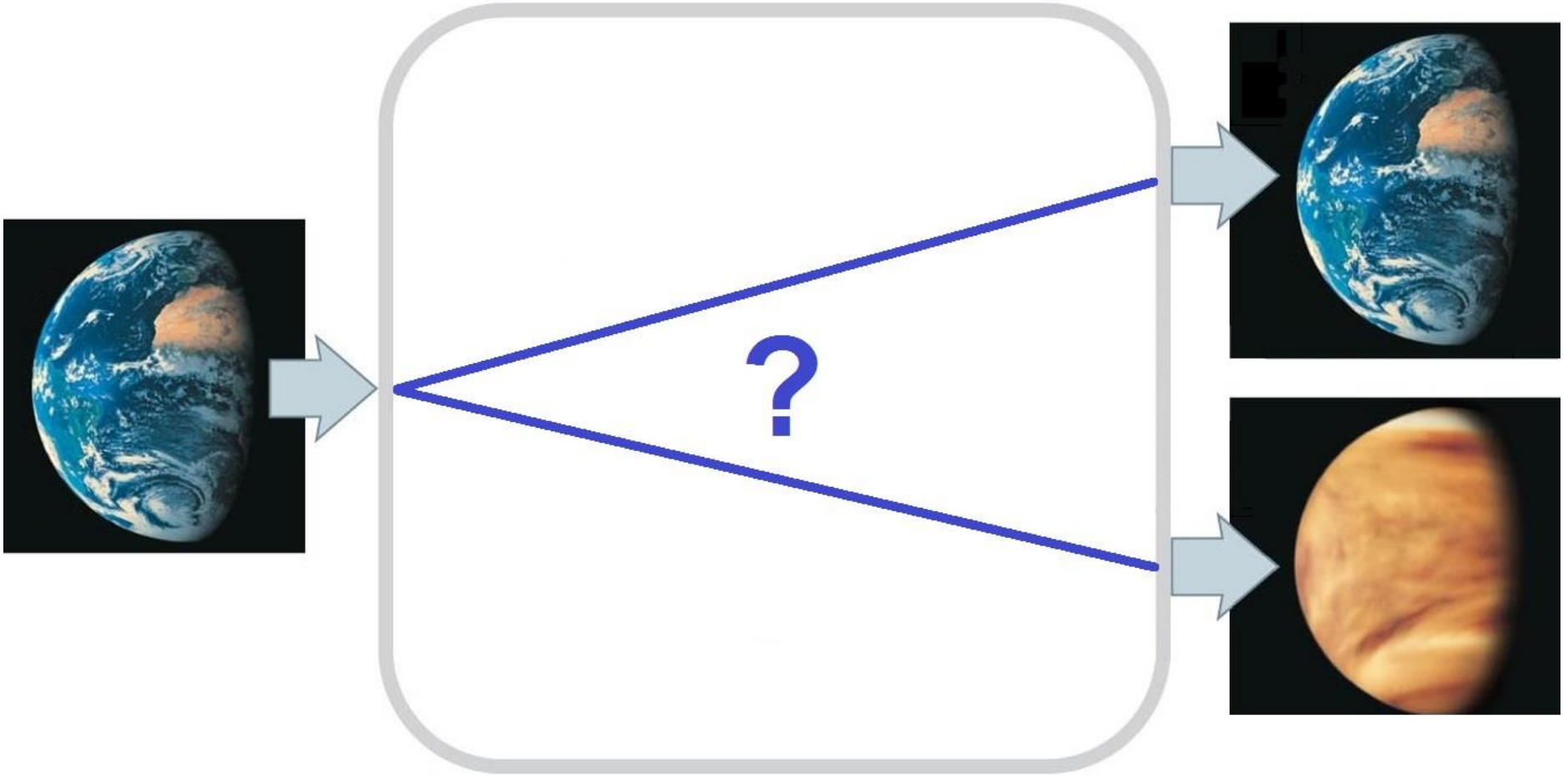


"the traditional concept of habitable zone ... is critical when we are searching for intelligent life"

Bennett & Shostak

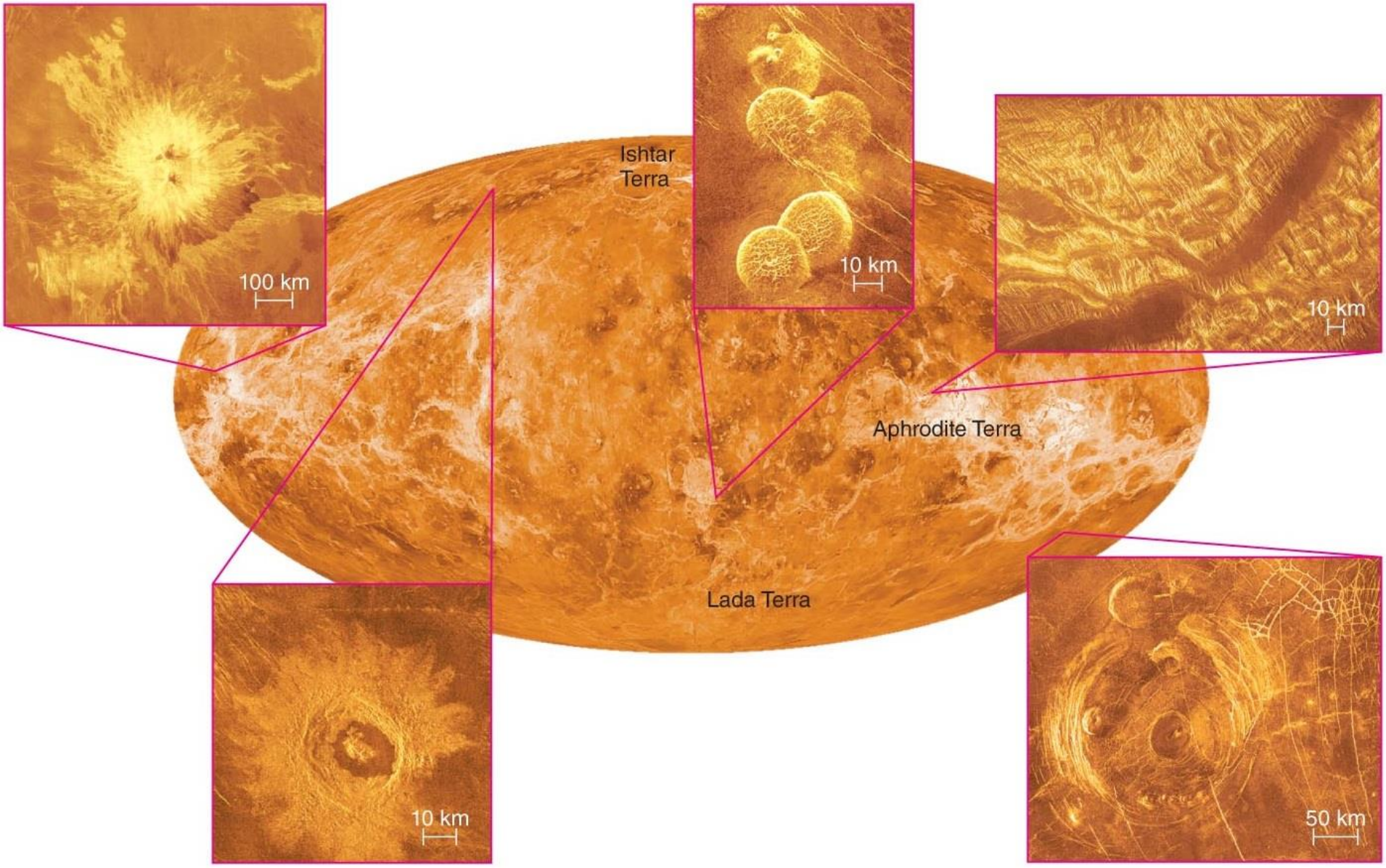

Venus
Earth
Mars
Sun
Jupiter
100 km
100 km
50 km
Earth's Moon
100 km

Earth habitable if Earth were at the orbit of Venus?

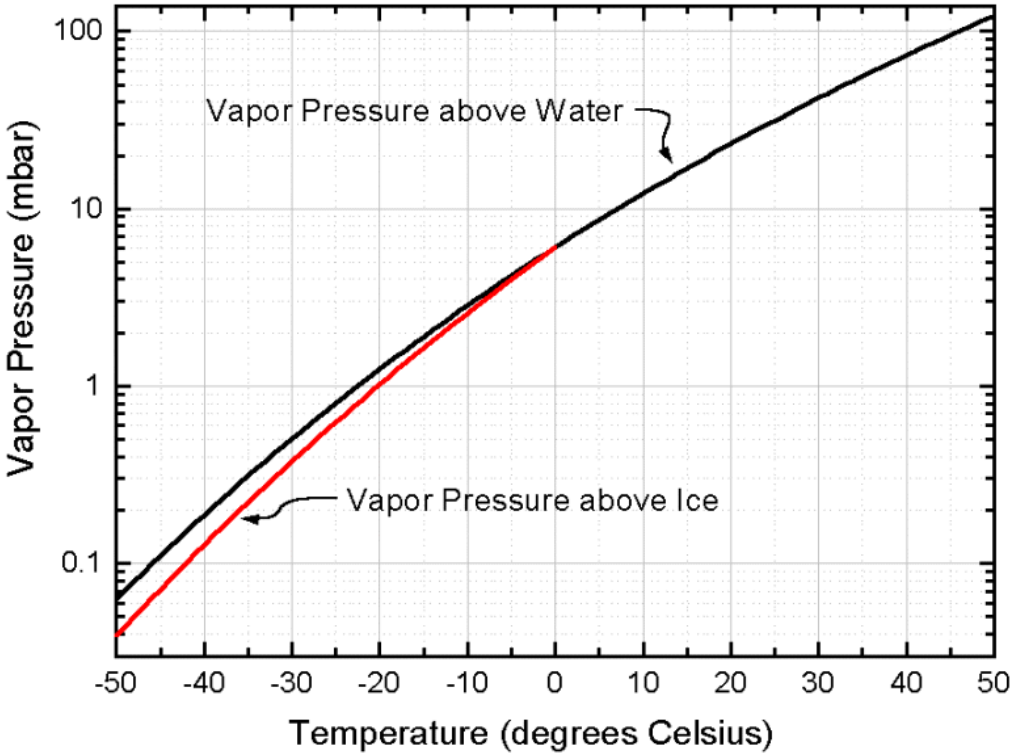


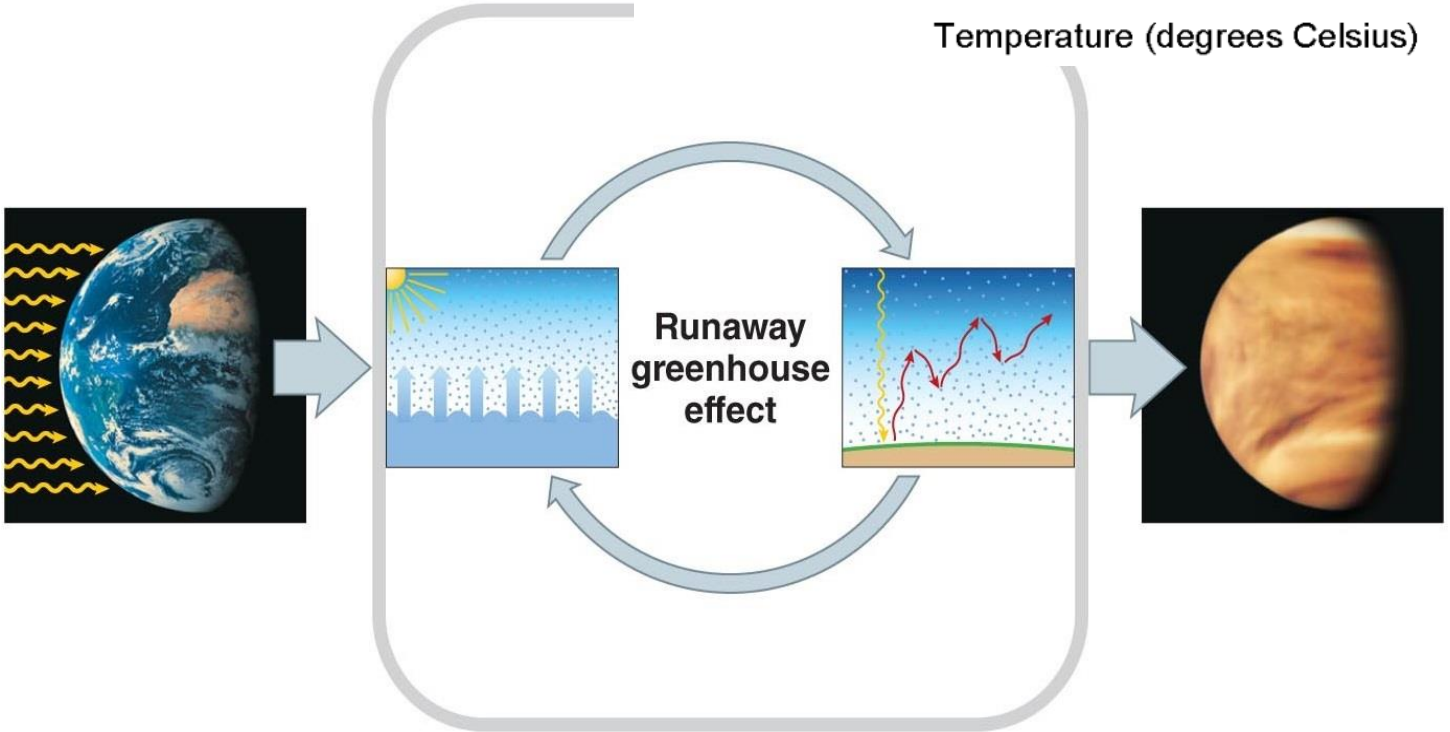
Due to solar irradiation, surface temperatures on Venus are 30°C higher than on Earth. During Cretaceous period, sea temperatures exceeded current levels by 17°C and deep sea temperatures were higher by 15°C to 20°C.

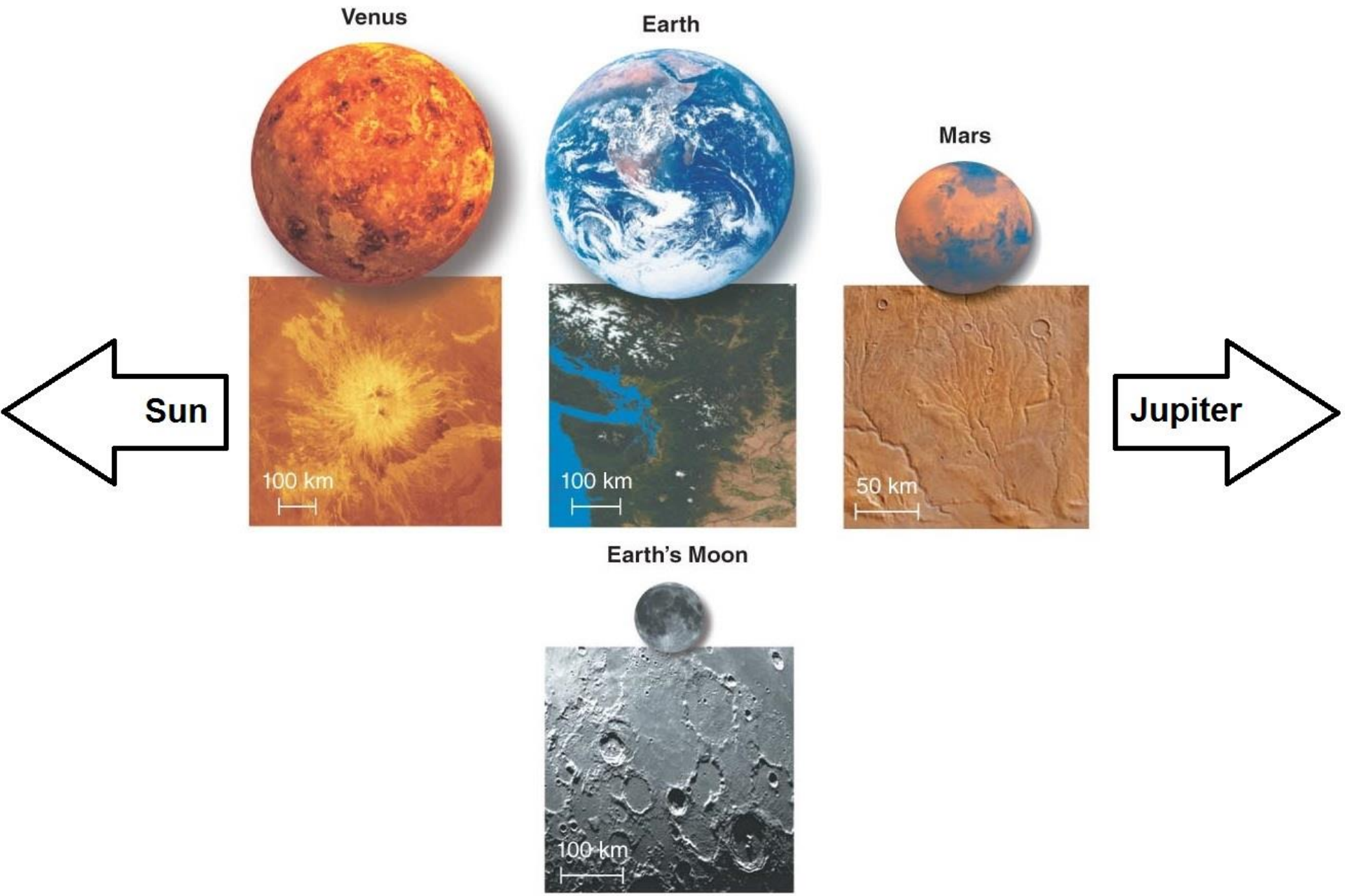
Venus also habitable?



Runaway Greenhouse Effect and Moist Greenhouse Effect



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Earth
Mars
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100 km
100 km
50 km
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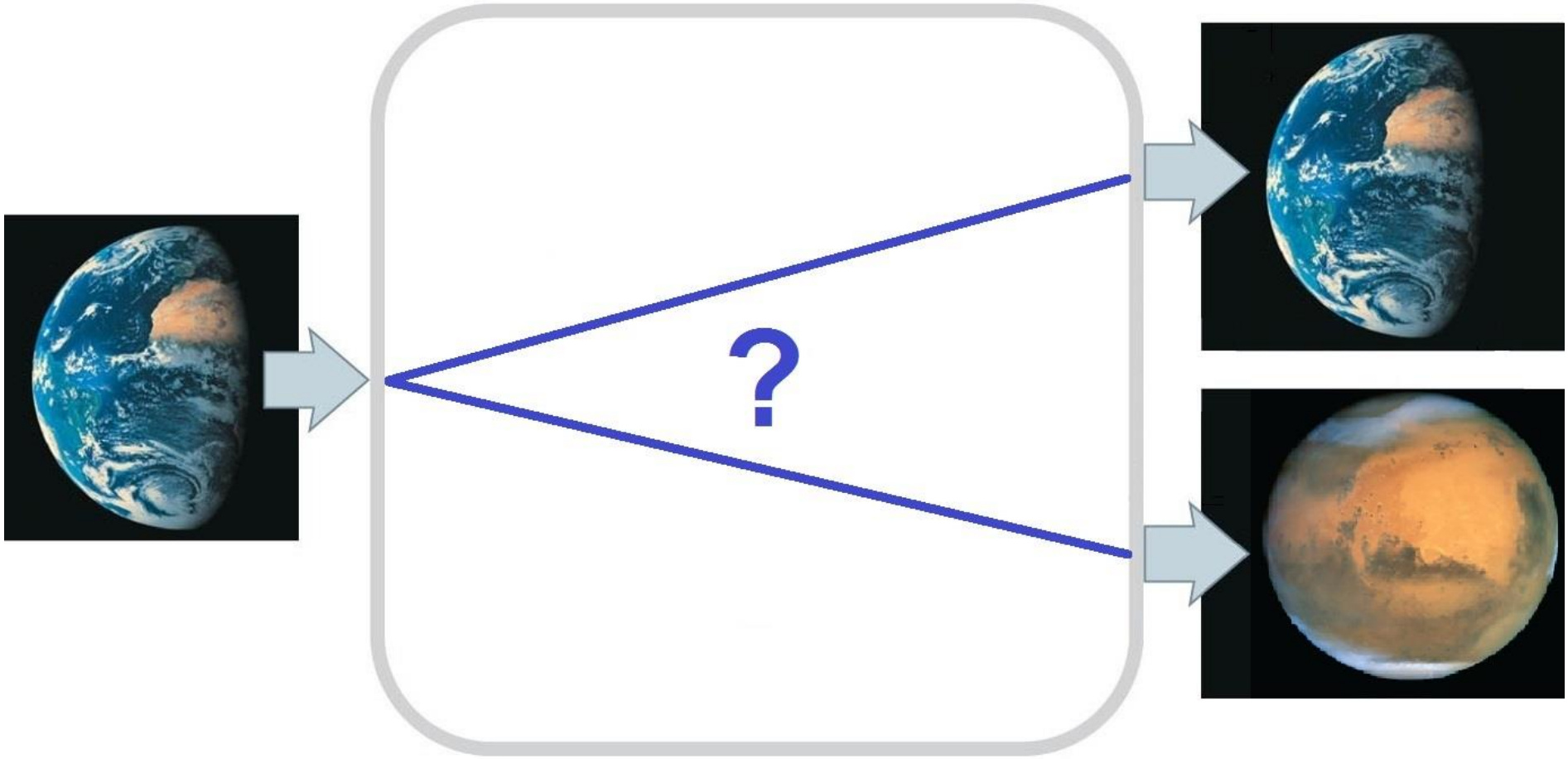
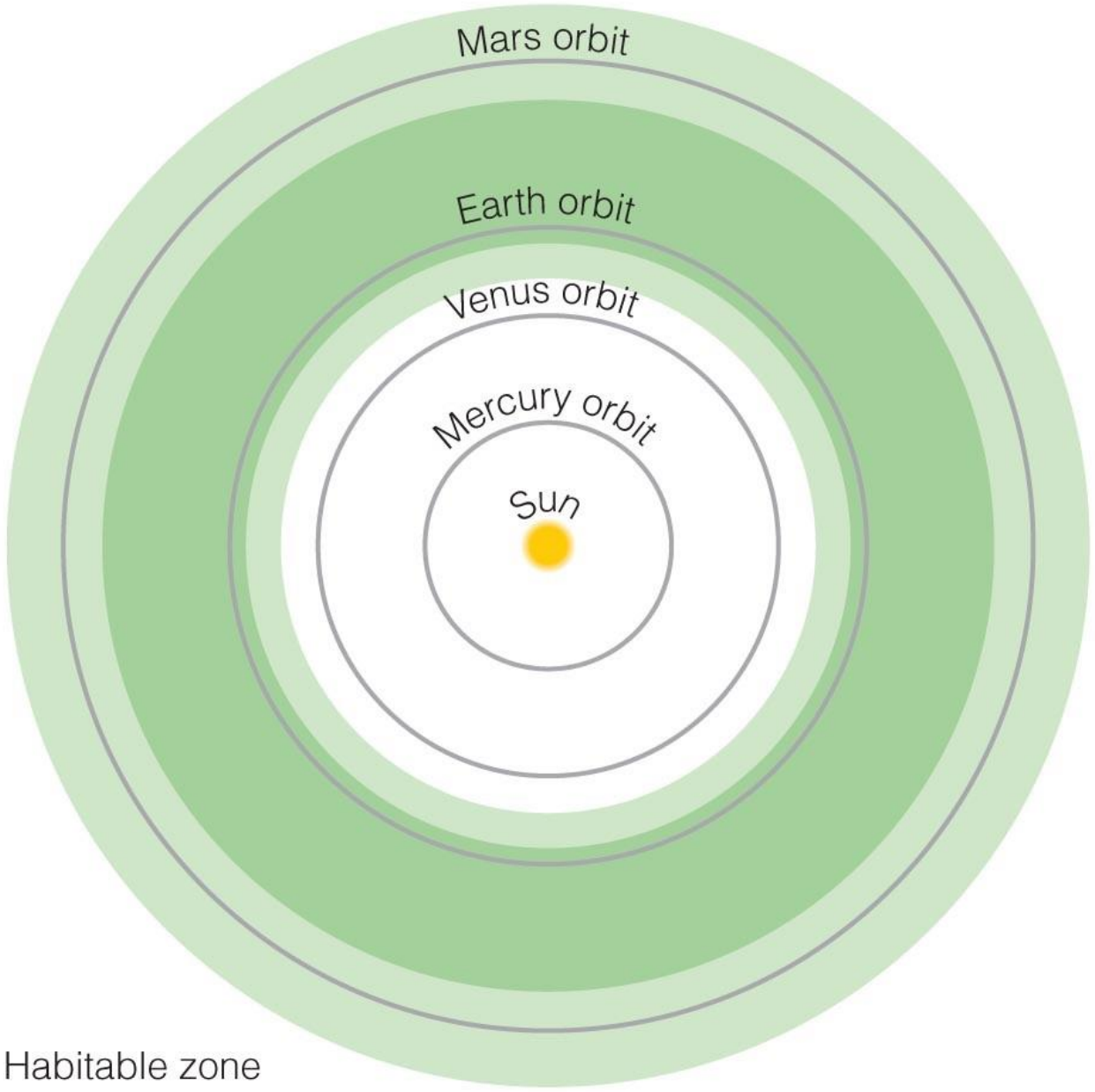
Earth habitable if Earth were at the orbit of Mars?

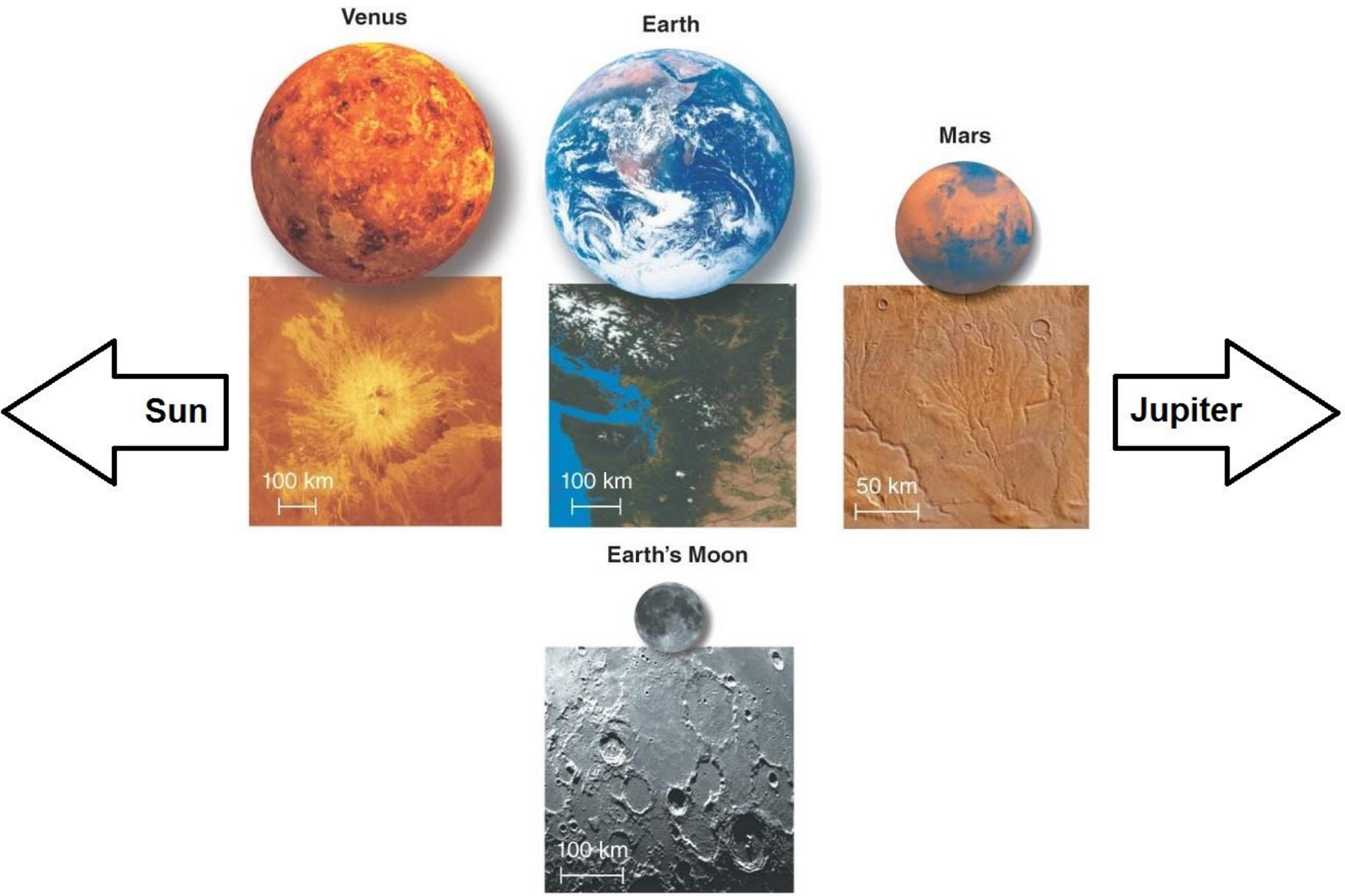




Habitable zone

conservative estimate

optimistic estimate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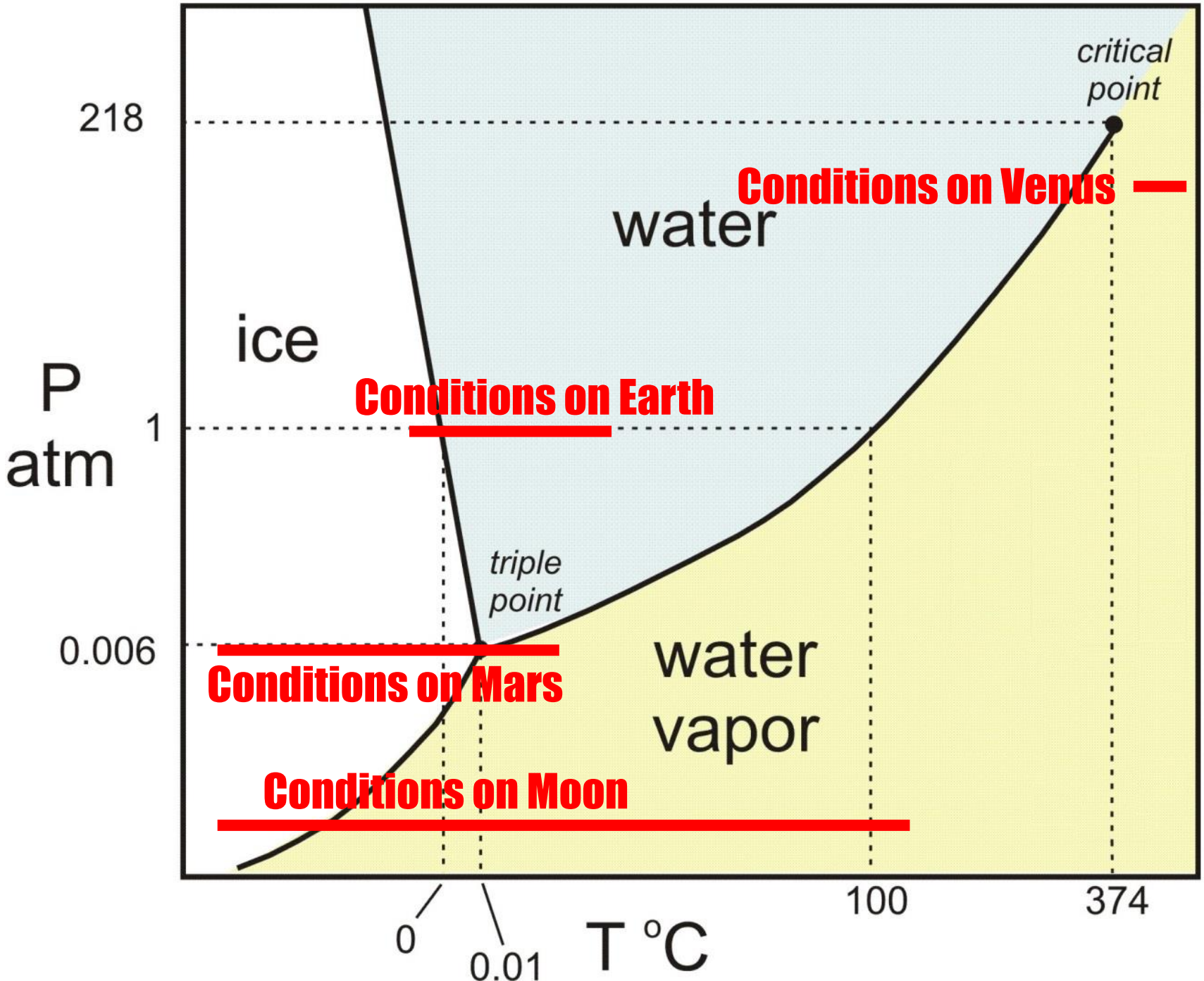
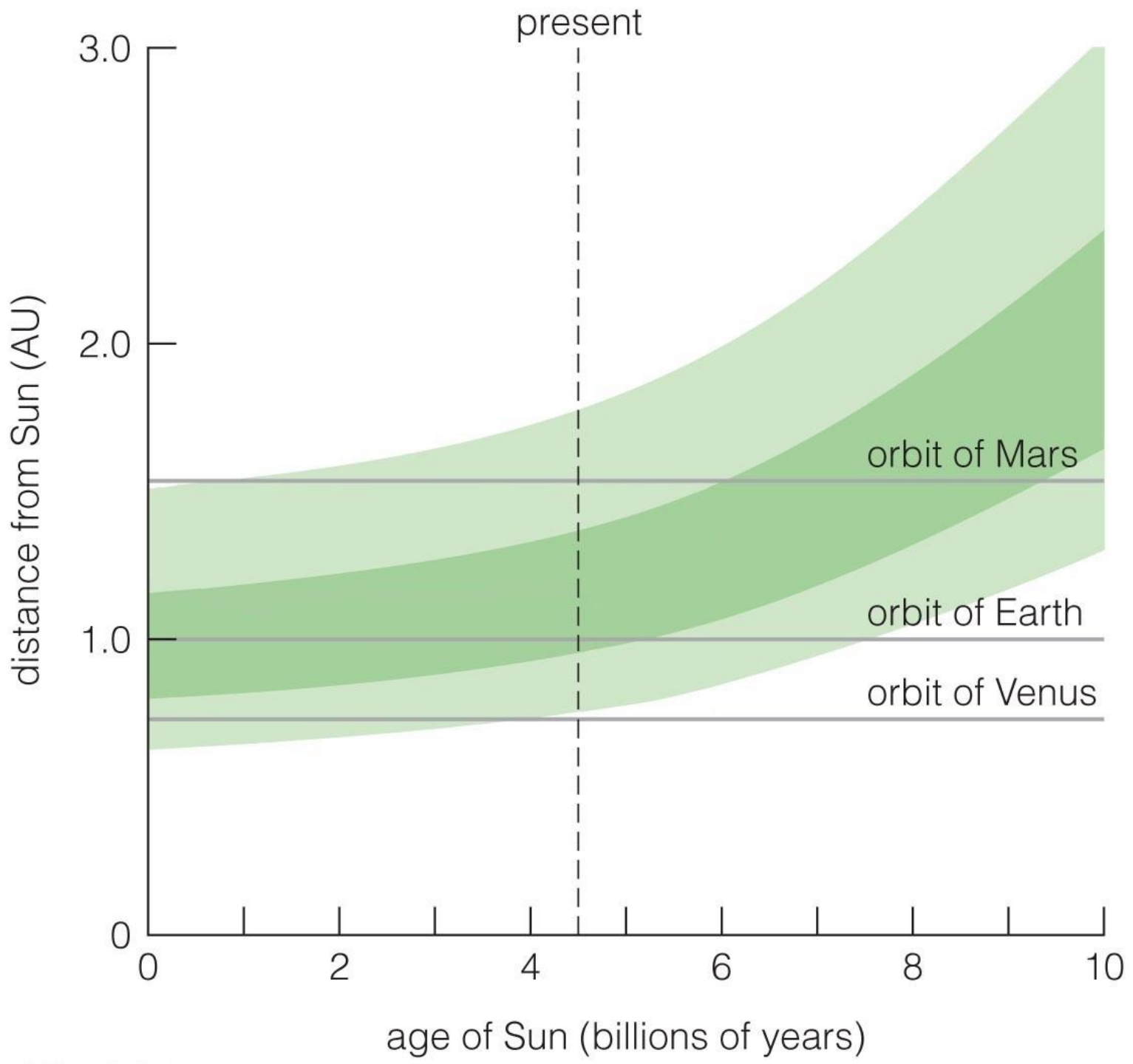
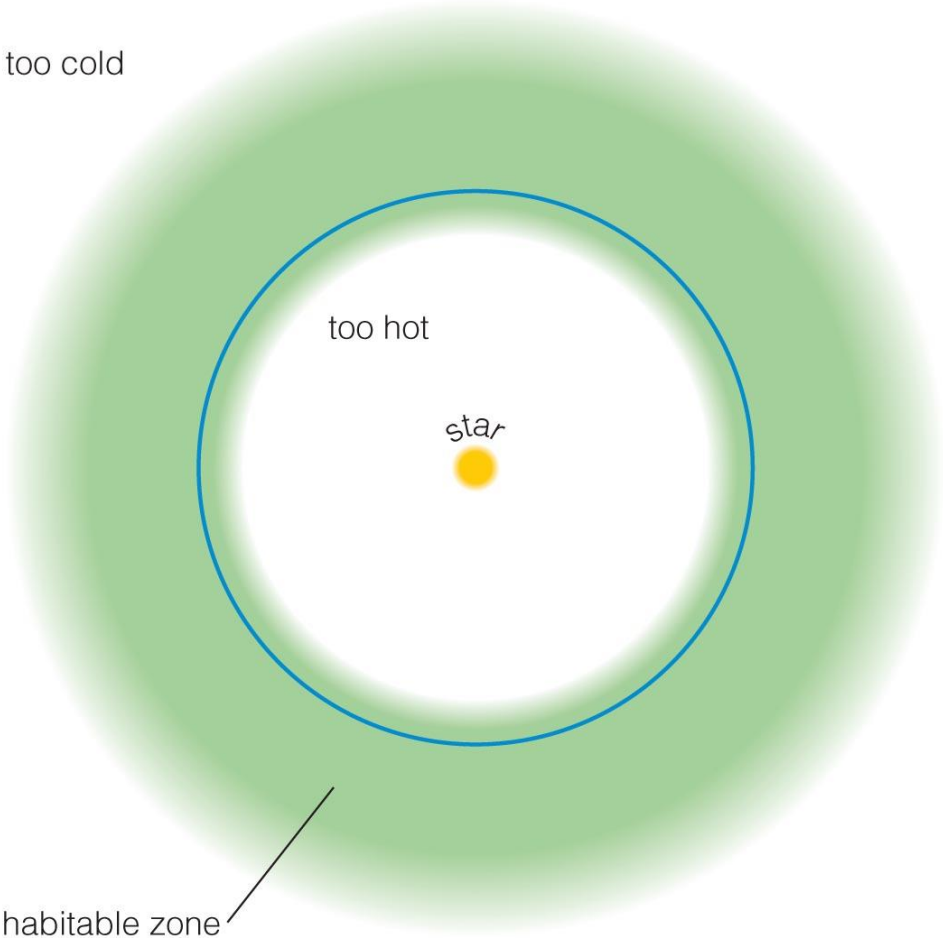

critical
point
218
Conditions on Venus
water
ice
P
atm
1
Conditions on Earth
triple
point
0.006
water
vapor
Conditions on Mars
Conditions on Moon
100
374
0
0.01
T °C


present
3.0
2.0
1.0
0
distance from Sun (AU)
orbit of Mars
orbit of Earth
orbit of Venus
0
2
4
6
8
10
age of Sun (billions of years)

The Concept of a Habitable Zone

- **Habitable zone:** range of distances at which worlds similar to Earth could exist.
  - Example: a region where a world *could have* liquid surface water
- Existing within a star's habitable zone is insufficient (e.g., Moon).
- Stars brighten as they age, causing habitable zones to evolve, moving outward from a star with time.

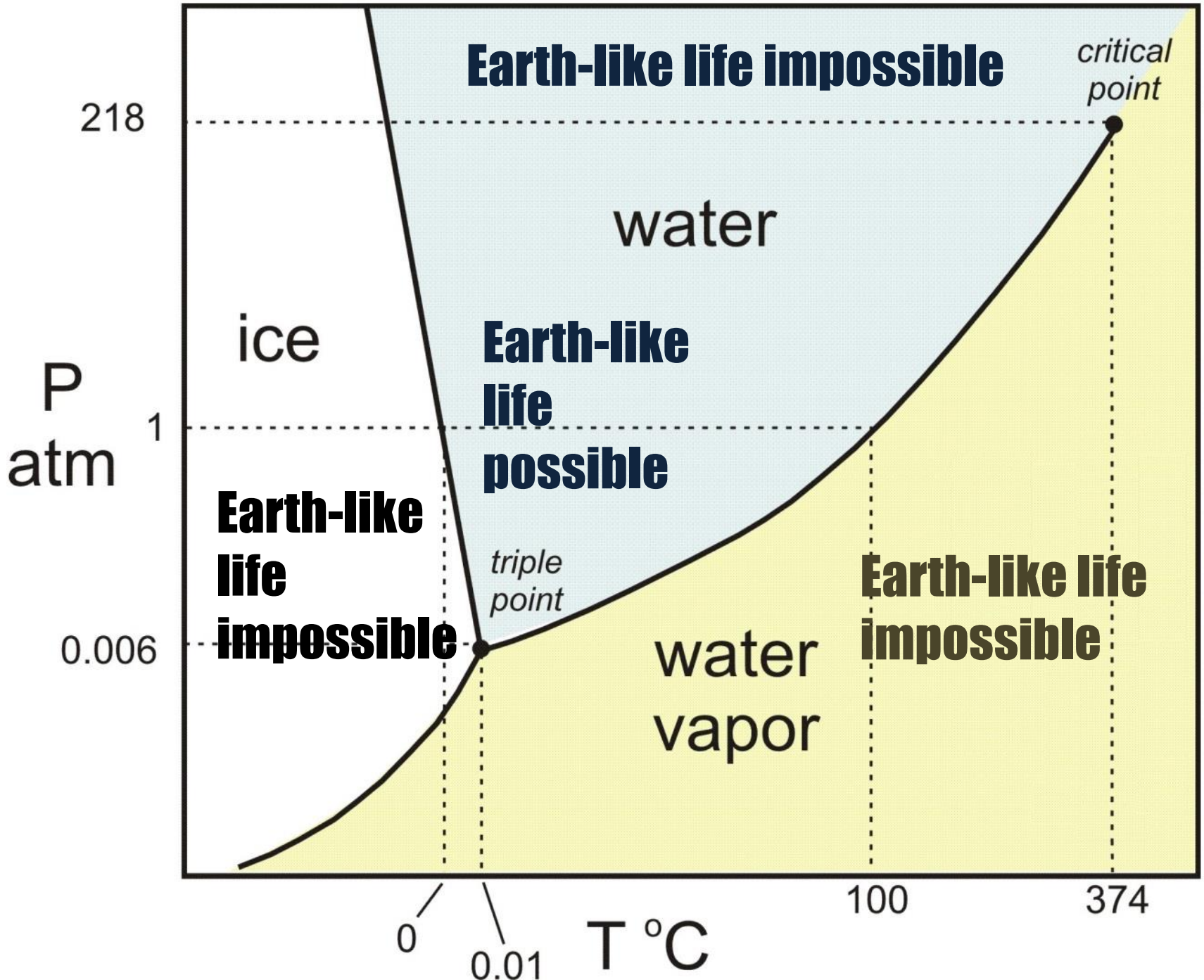


Life Outside the Habitable Zone

- Life can exist outside a habitable zone.
  - **Mars**: Pockets of subsurface liquid water heated by geological mechanisms could provide necessary conditions for life.
  - **Europa**, **Ganymede**, and **Enceladus** provide evidence of liquid water heated via radioactive decay and tidal resonances.
  - **Rogue planets**, orphaned worlds thrown from their forming protoplanetary disk, number, at minimum, in the billions.

Life Outside the Habitable Zone

- An Earth-sized world with no star could maintain a thick hydrogen atmosphere, insulating planetary heat and keeping oceans liquid.
- **Titan** and its liquid ethane, methane, and ammonia, also give possible conditions for life outside the habitable zone, expanding the number of moons capable of supporting life.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218
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Earth-like life possible
P atm
1
Earth-like life impossible
triple point
0.006
water vapor
Earth-like life impossible
100
374
0
0.01
T °C

	Description	*Key Advantages*	*Major Limitations*
Direct Detection	Obtain images or spectra of extrasolar planets	• Is the only method that allows direct study of the planets themselves	• Requires large telescopes and some means of blocking light from star planet is orbiting
Astrometric Method	Infer planet's existence from small changes in star's position in sky	• Is now possible with *GAIA* spacecraft • Detects planets in all orbit orientations except edge-on	• Is generally possible only for relatively nearby stars • Is biased toward finding massive planets that orbit far from their stars • May require many years of observation to detect these planets (with large orbital periods)
Doppler Method	Infer planet's existence from star's motion toward/away from us as revealed by Doppler shifts in its spectrum	• Is possible from ground-based telescopes • Detects planets in all orbit orientations except face-on	• Is biased toward finding massive planets with close-in orbits • Underestimates star's true motion except when system is viewed edge-on • Requires stellar spectra, which means large telescopes and long observation times
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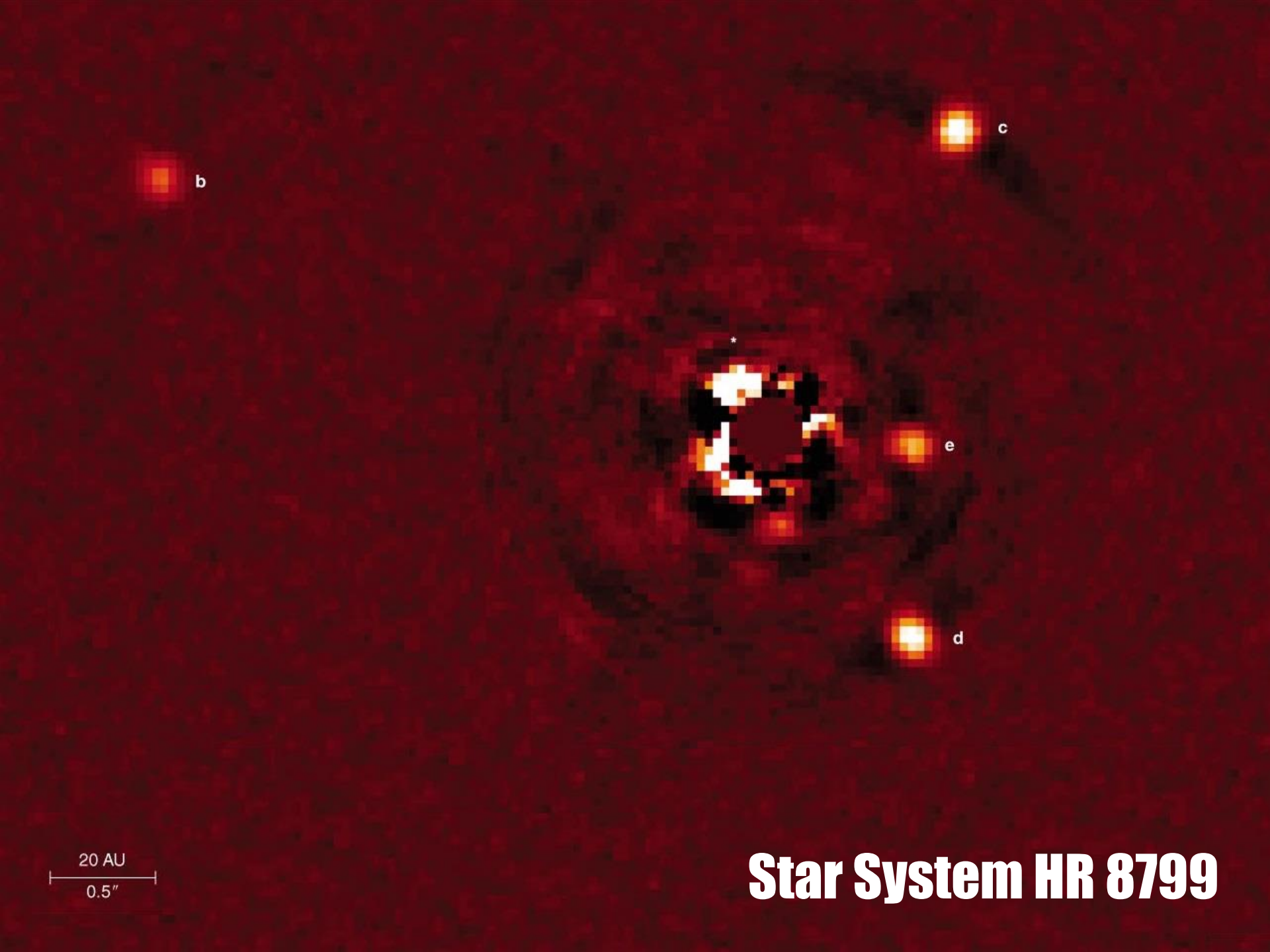

Star System HR 8799

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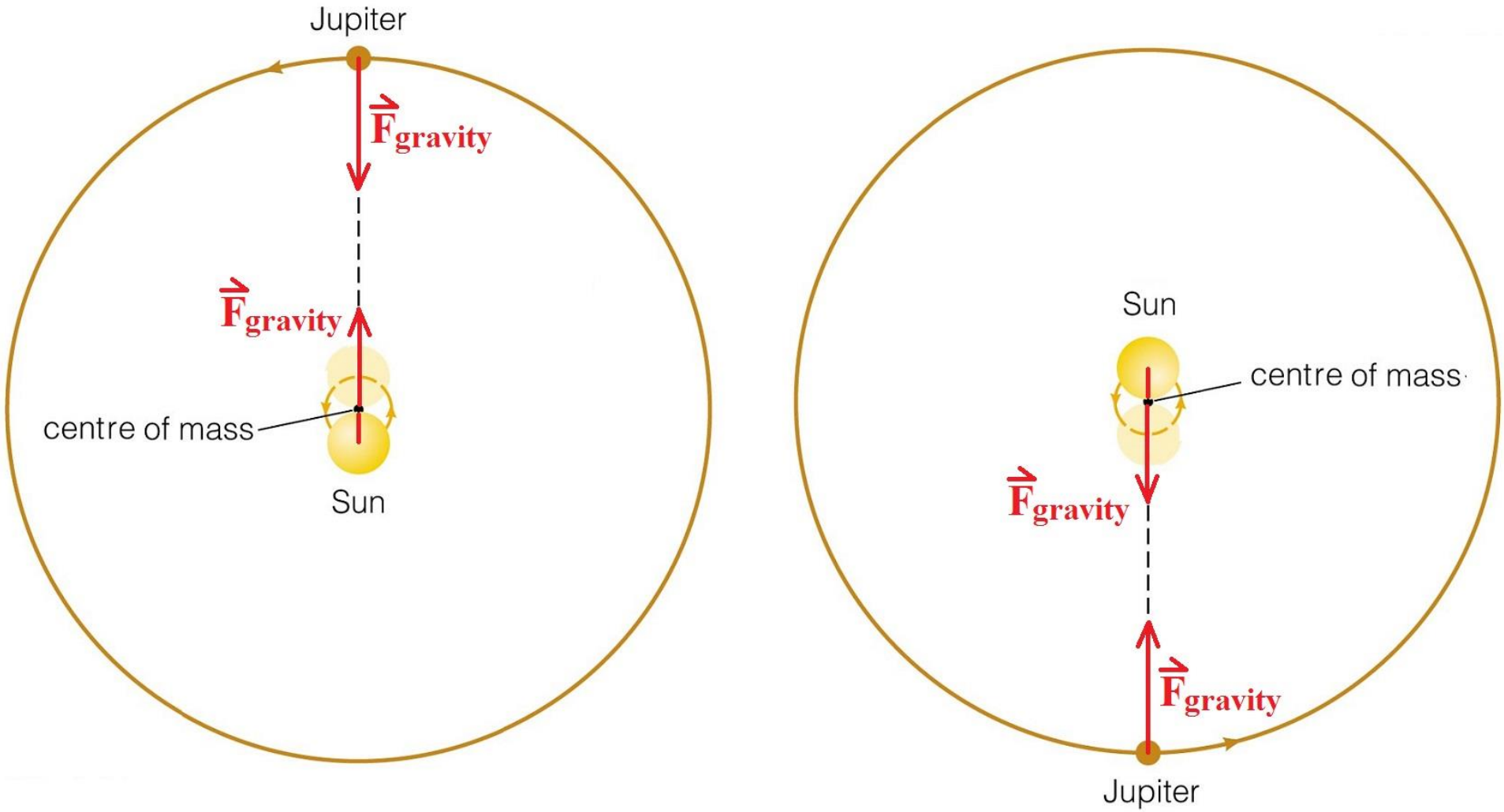
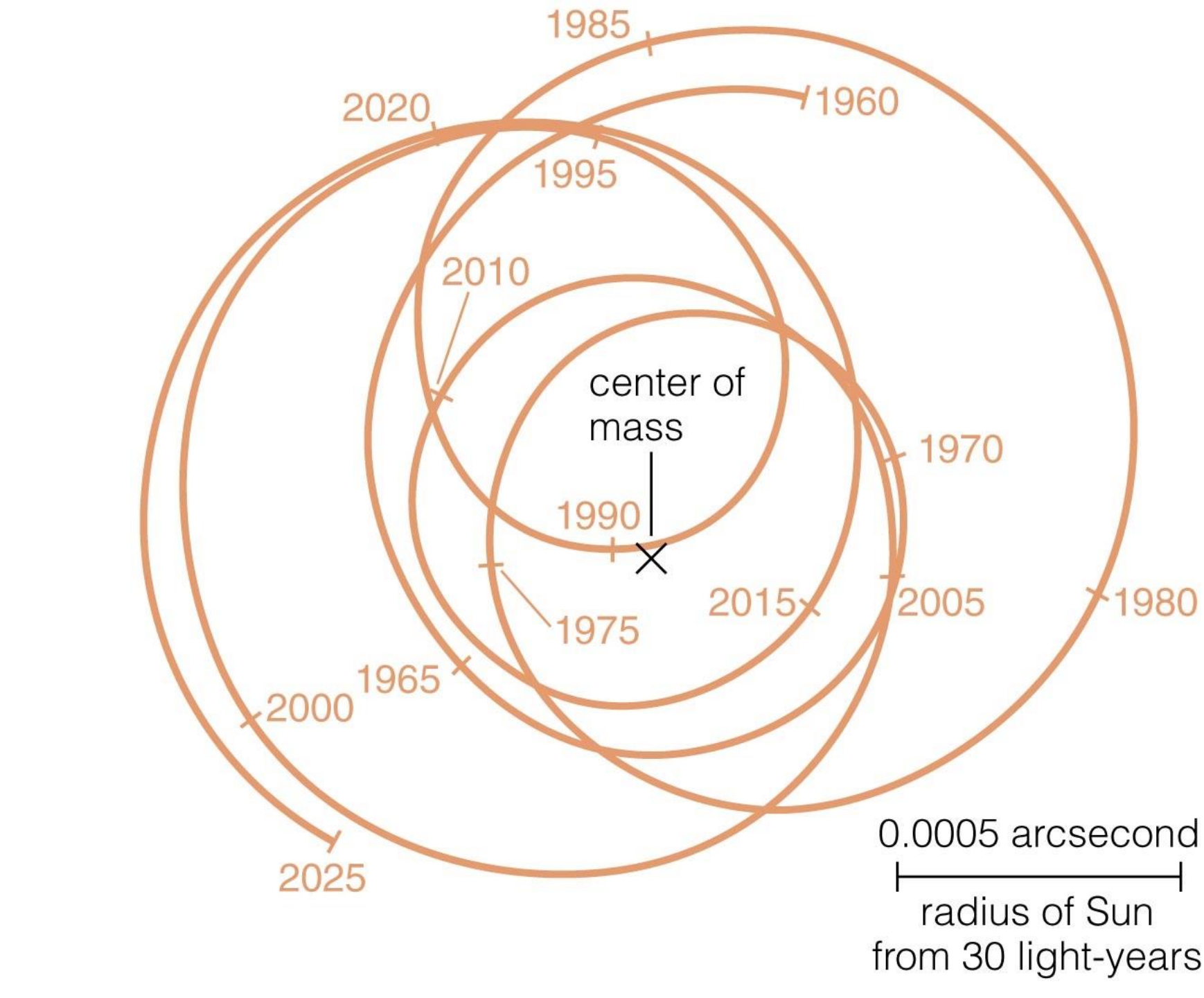


t = 0

T: period

t = T/2


1985
1960
2020
1995
2010
center of
mass
1970
1990
2015
2005
1980
1975
1965
2000
2025
0.0005 arcsecond
radius of Sun
from 30 light-years

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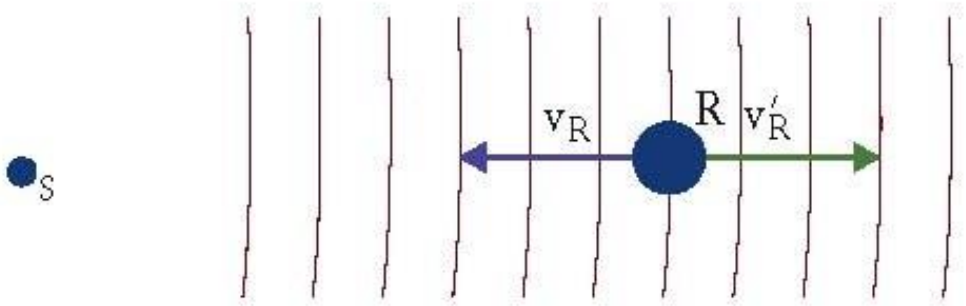
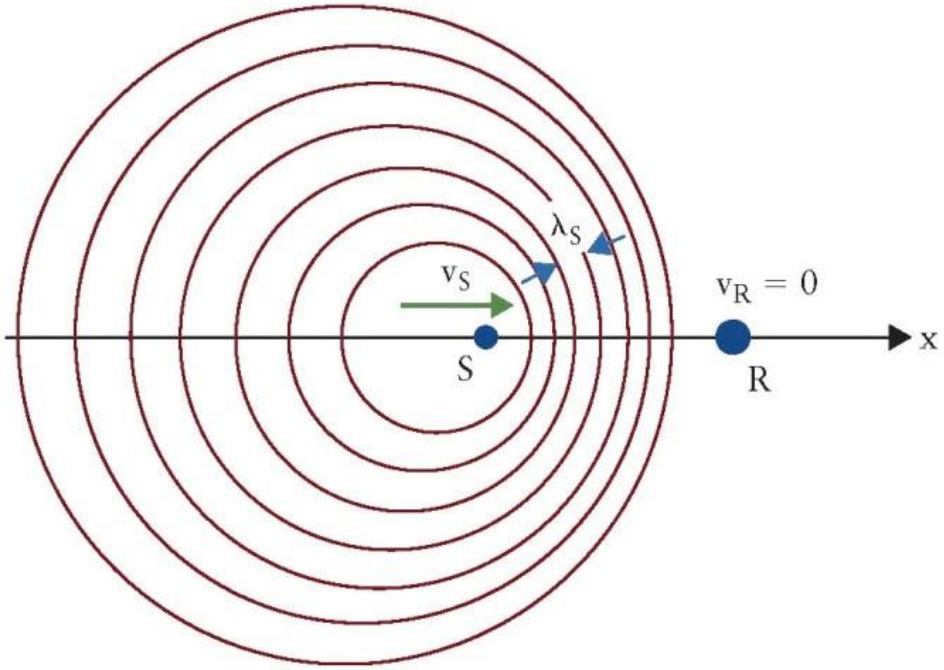
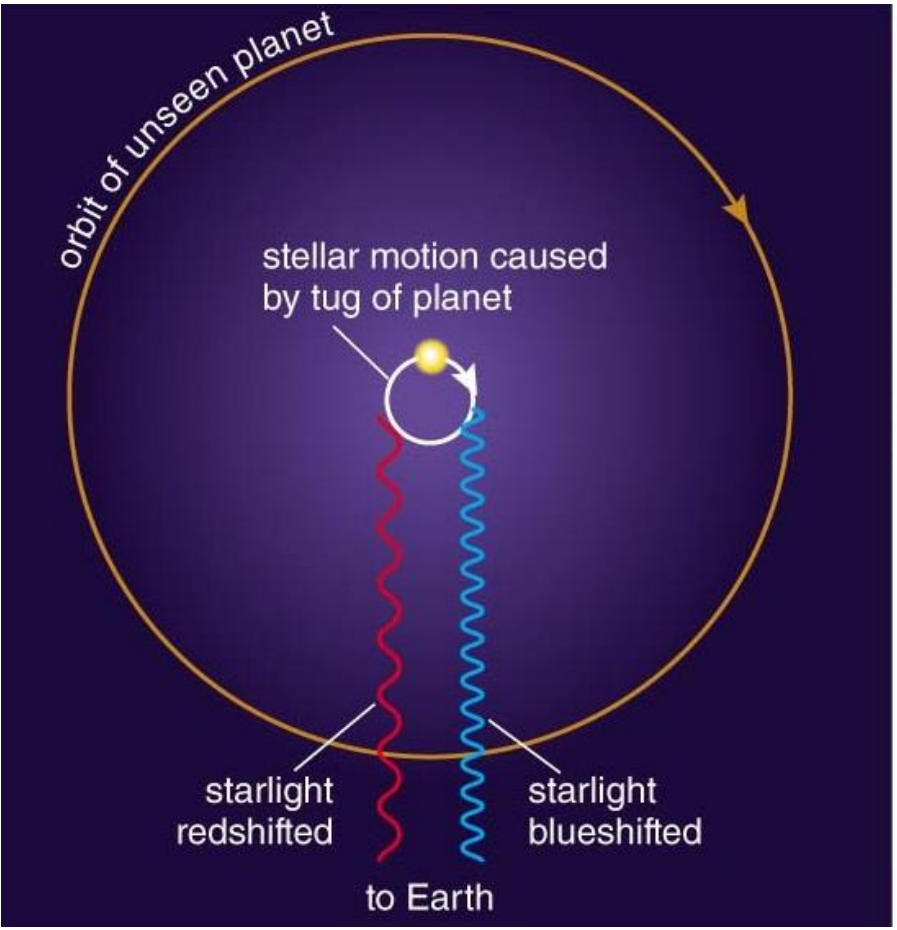
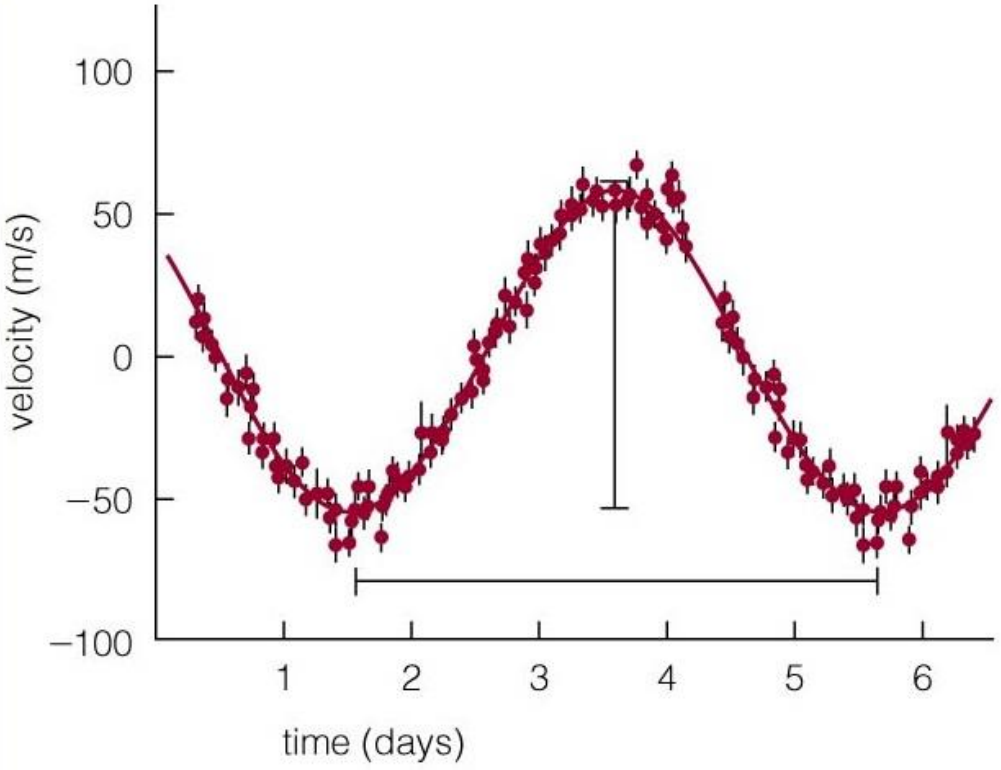
Doppler Ultrasound:
The use of the Doppler effect in Medicine





Doppler Measurement 51 Pegasus (1995)





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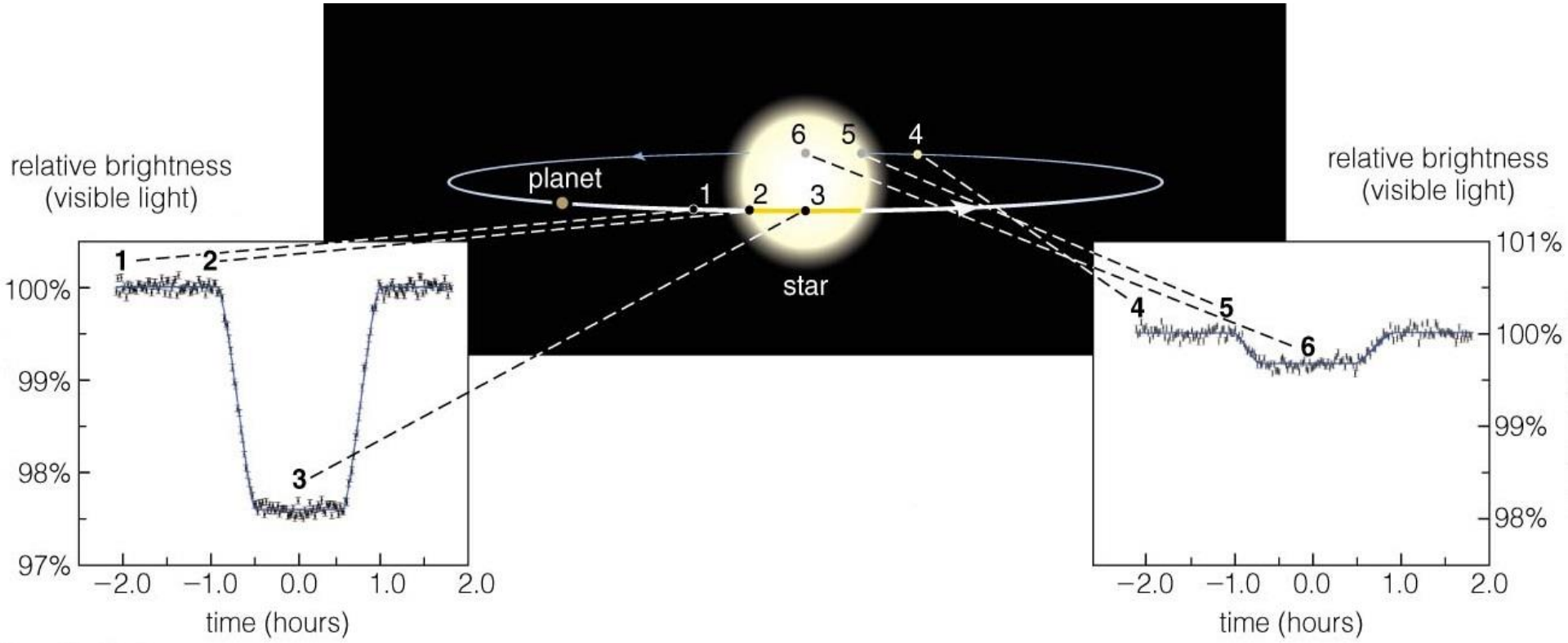
Venus Transit

Star System HD189733



Transit

Eclipse

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Orbital Properties	**period**	Doppler, astrometric, or transit	We directly measure orbital period
	distance	Doppler, astrometric, or transit	We calculate orbital distance from orbital period using Newton's version of Kepler's third law
	eccentricity	Doppler or astrometric	Velocity curves and astrometric star positions reveal eccentricity
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Physical Properties	**mass**	astrometric or Doppler	We calculate mass based on the amount of stellar motion caused by the planet's gravitational tug
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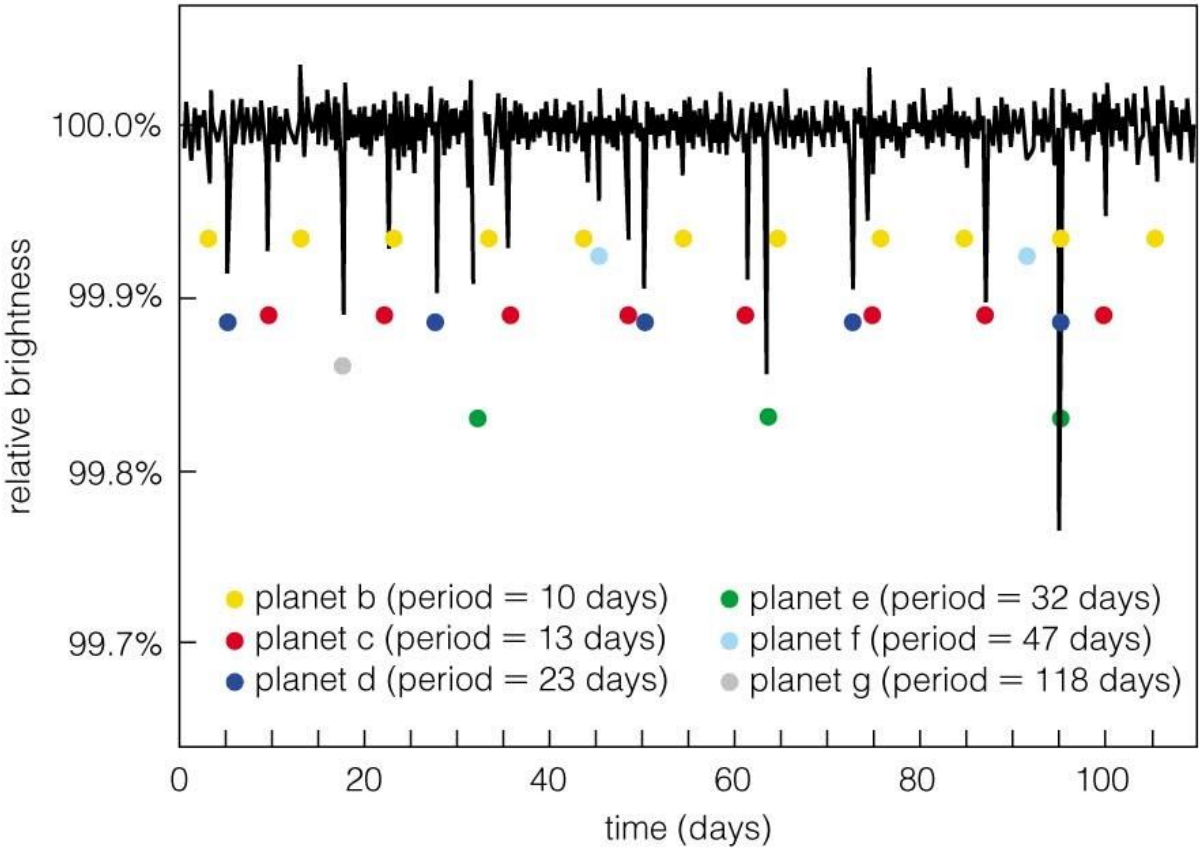
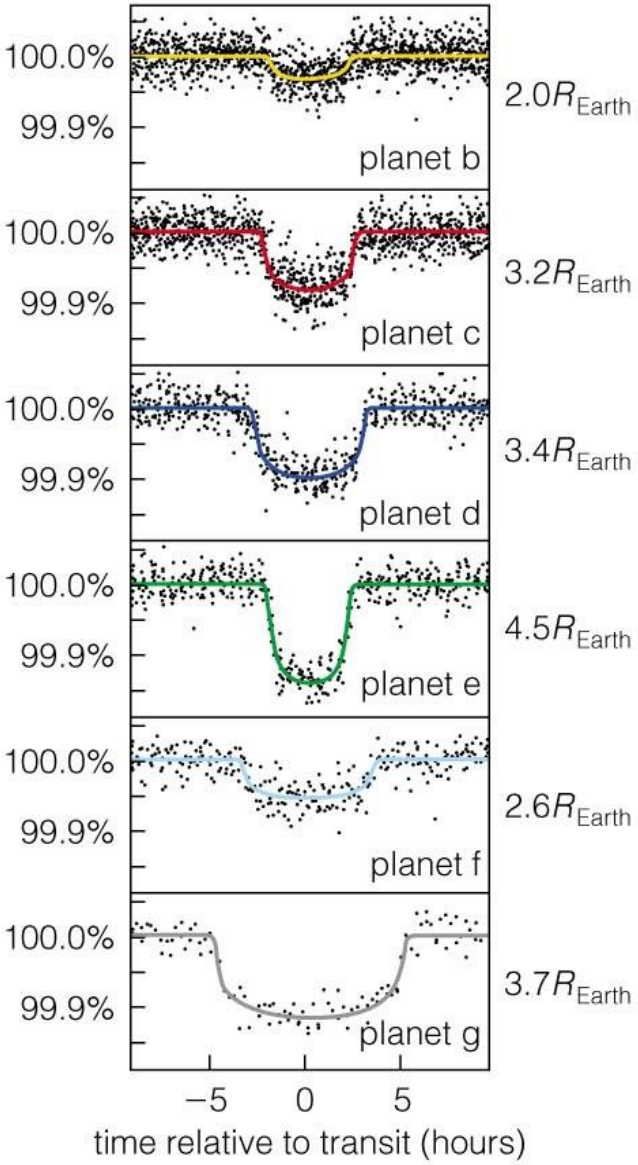
	atmospheric composition and temperature	transit or direct detection	Transits and eclipses provide data on atmospheric composition and temperature

Star System Kepler 11





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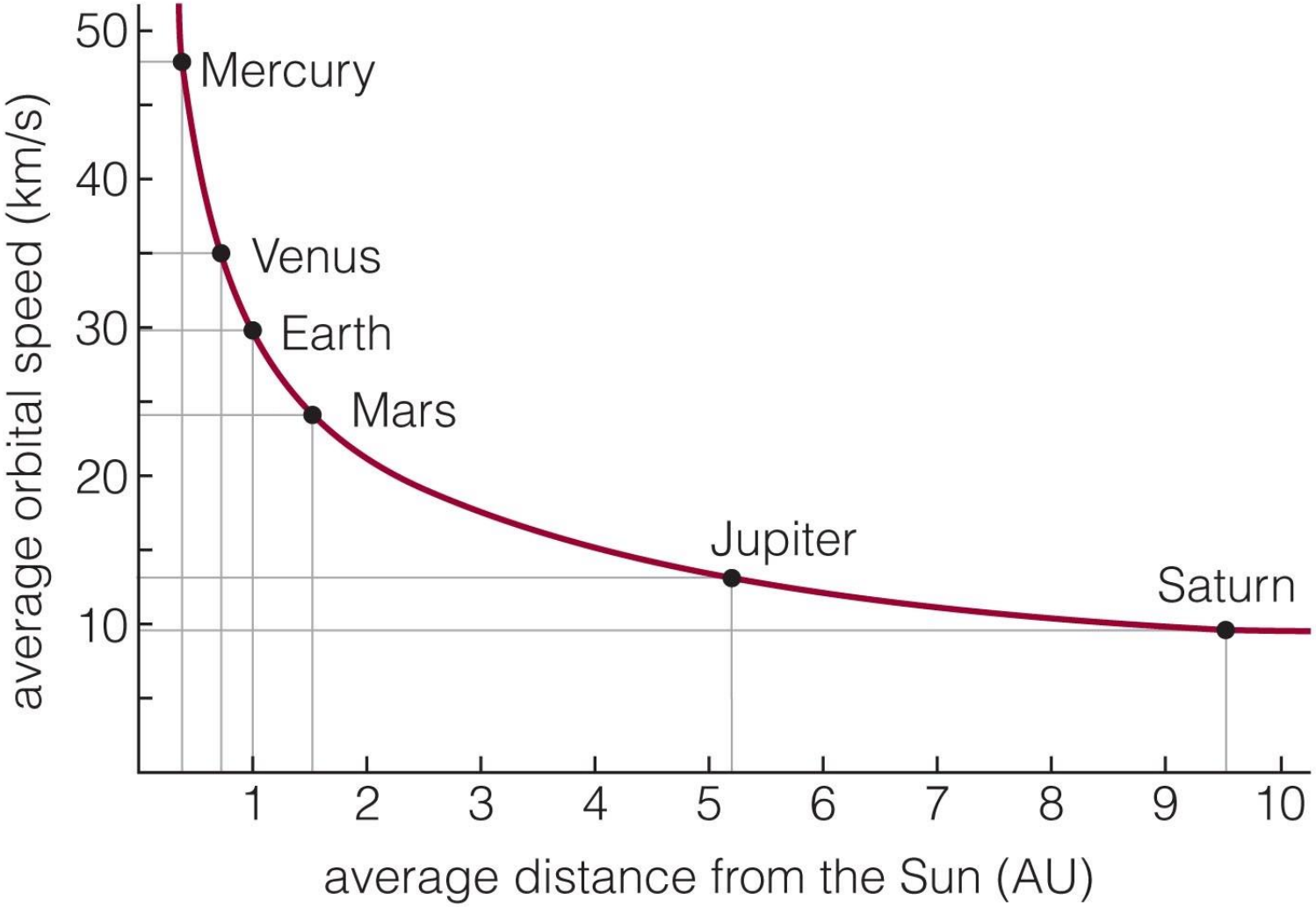

Kepler's Third Law (1619): Quantitative Relation between orbital period p and average distance a:

p^2 proportional to a^3

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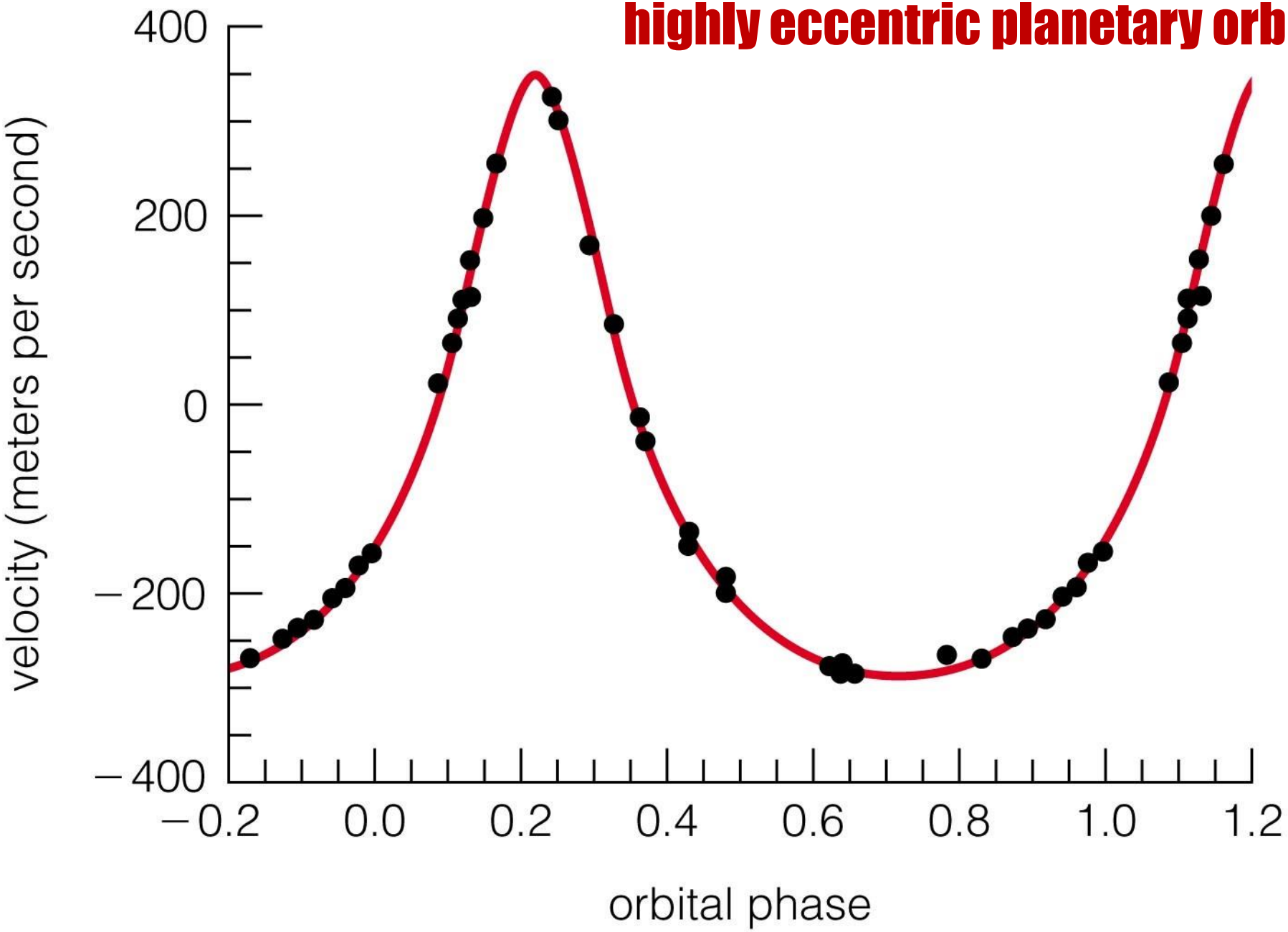
Doppler velocity measurement 70 Virginis: highly eccentric planetary orbit



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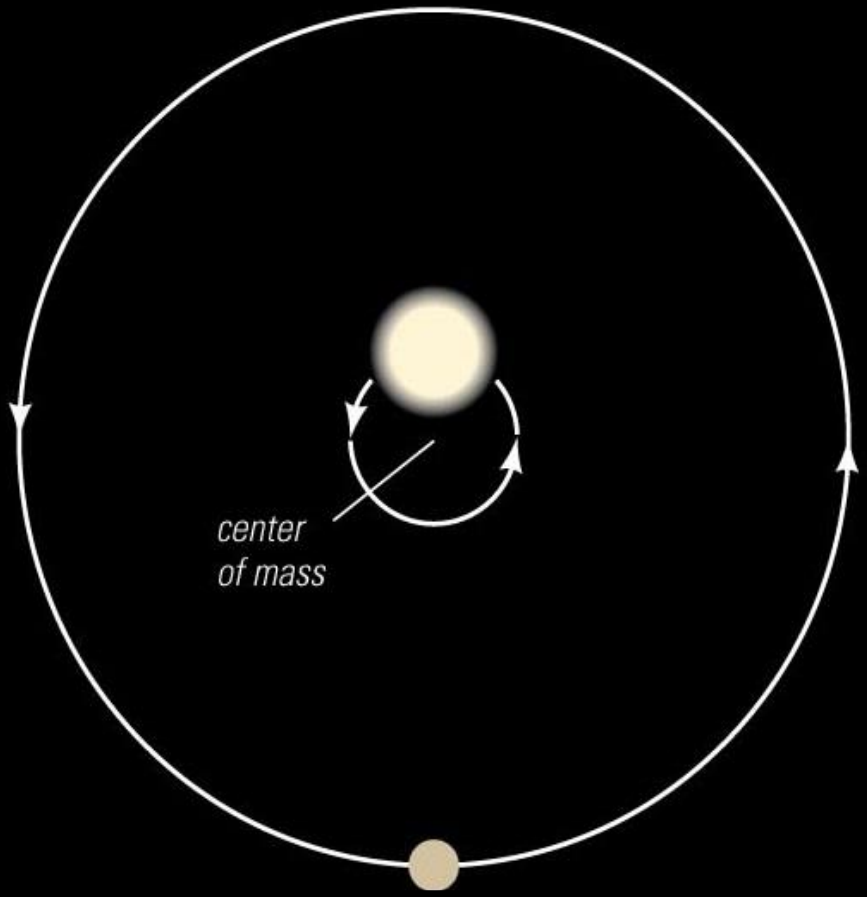
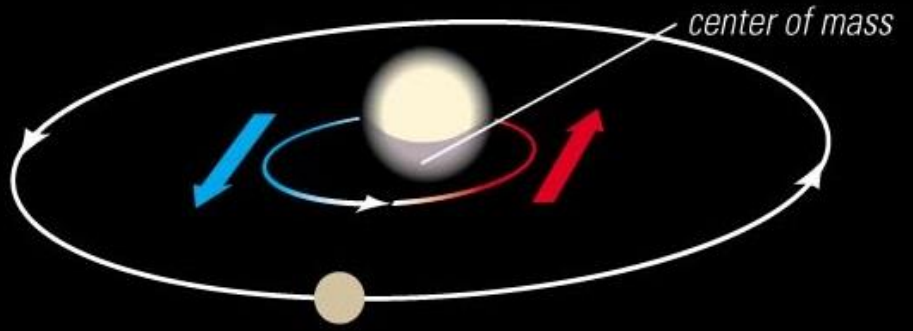
Orientation of a planetary plane relative to an observer on Earth matters for Doppler effect





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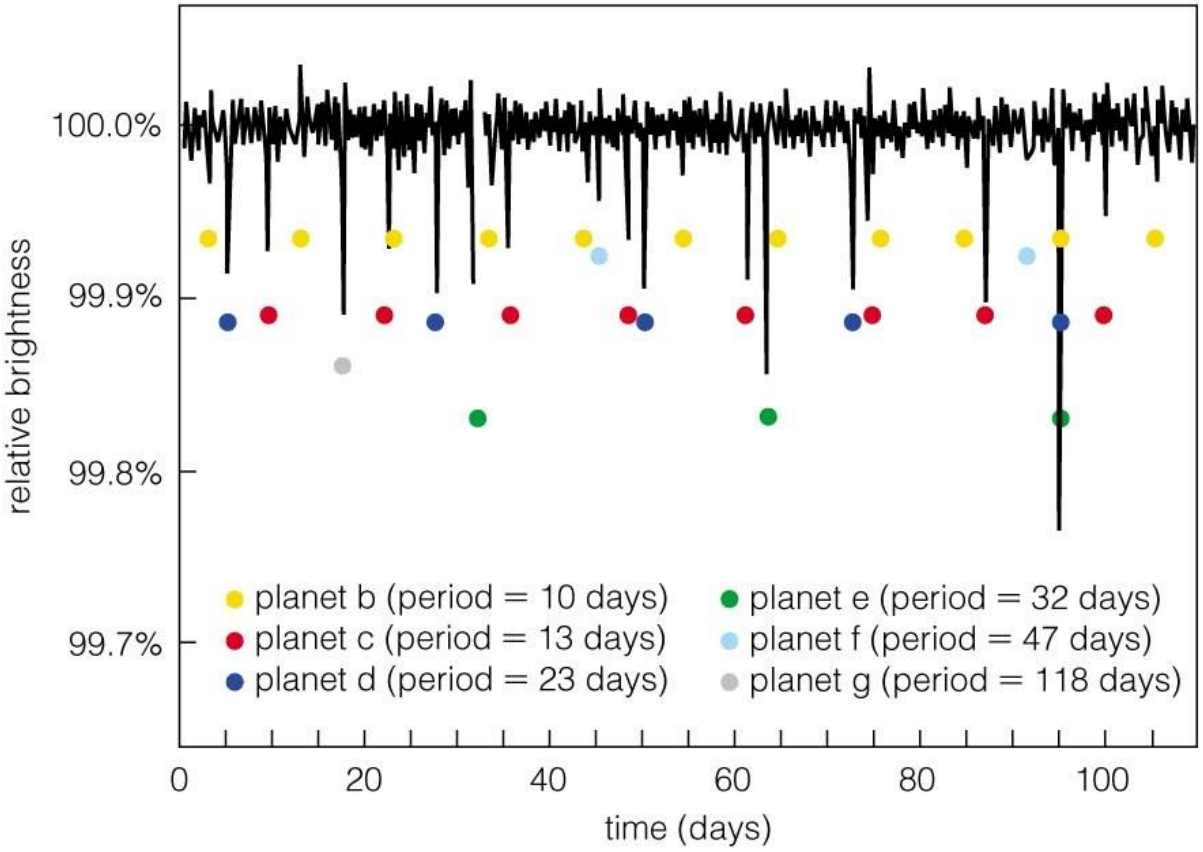
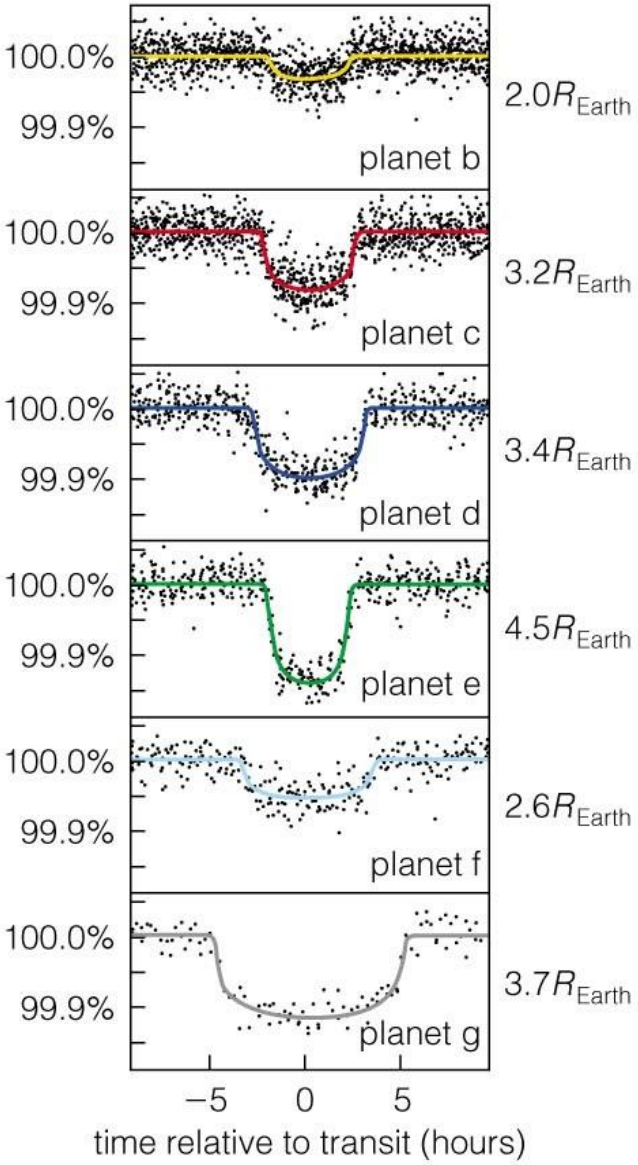
Star System Kepler 11





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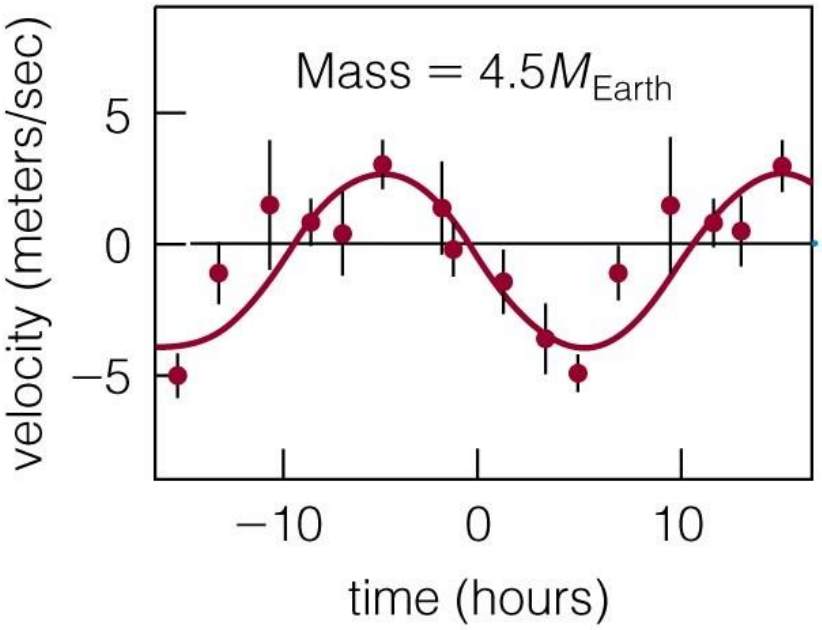
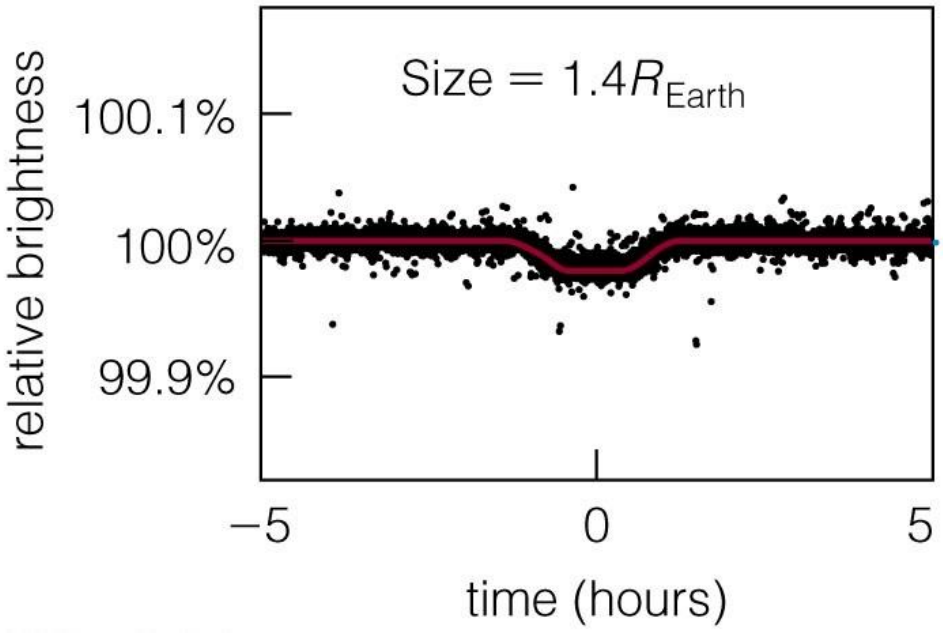
	atmospheric composition and temperature	transit or direct detection	Transits and eclipses provide data on atmospheric composition and temperature



For transiting planets, the Doppler method gives an accurate mass

planet density:

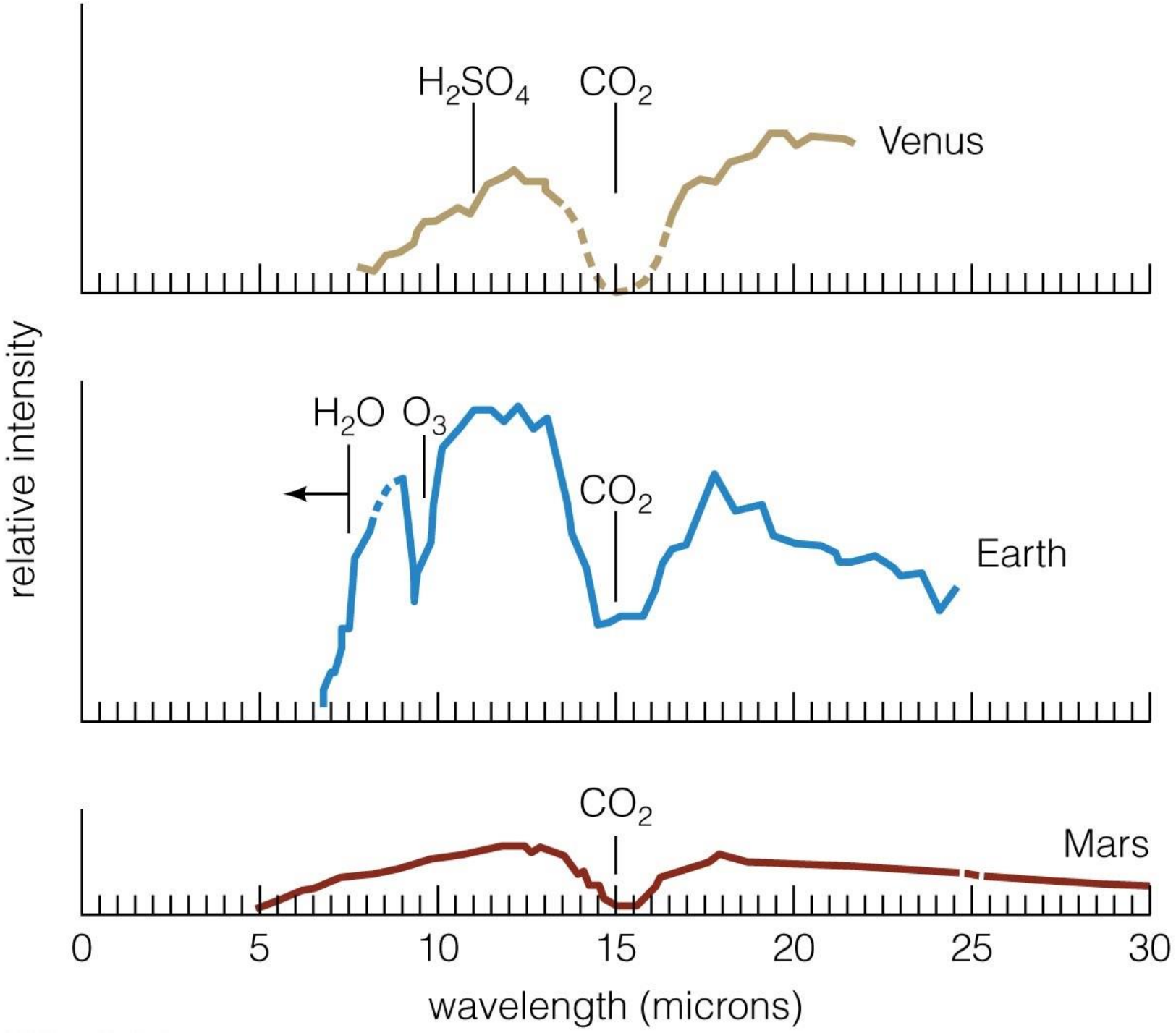
$$\frac{\text{mass}}{\text{volume}} = 8.8\ \text{g/cm}^3$$



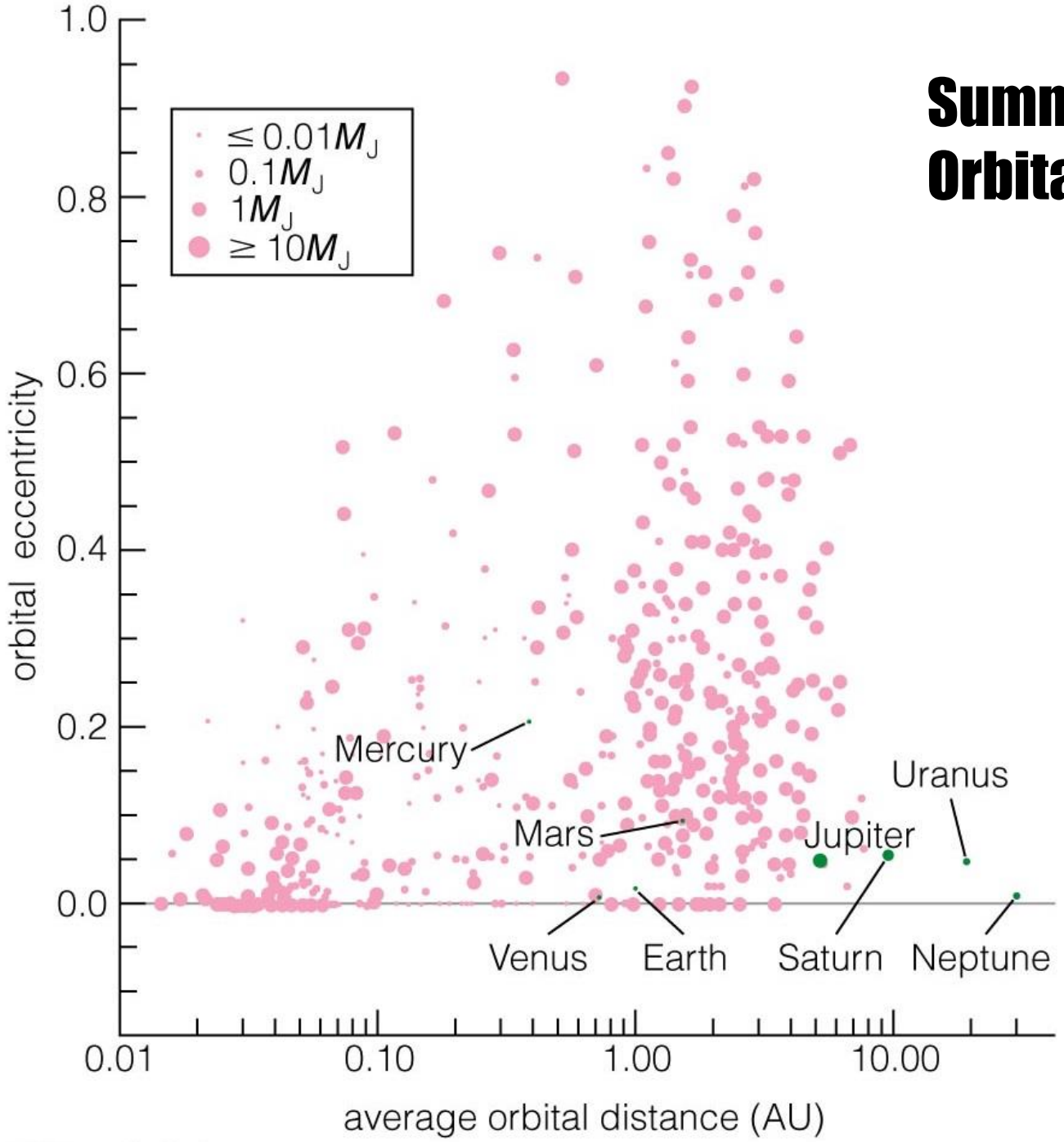
The transit method yields a radius, from which we can calculate the planet's volume

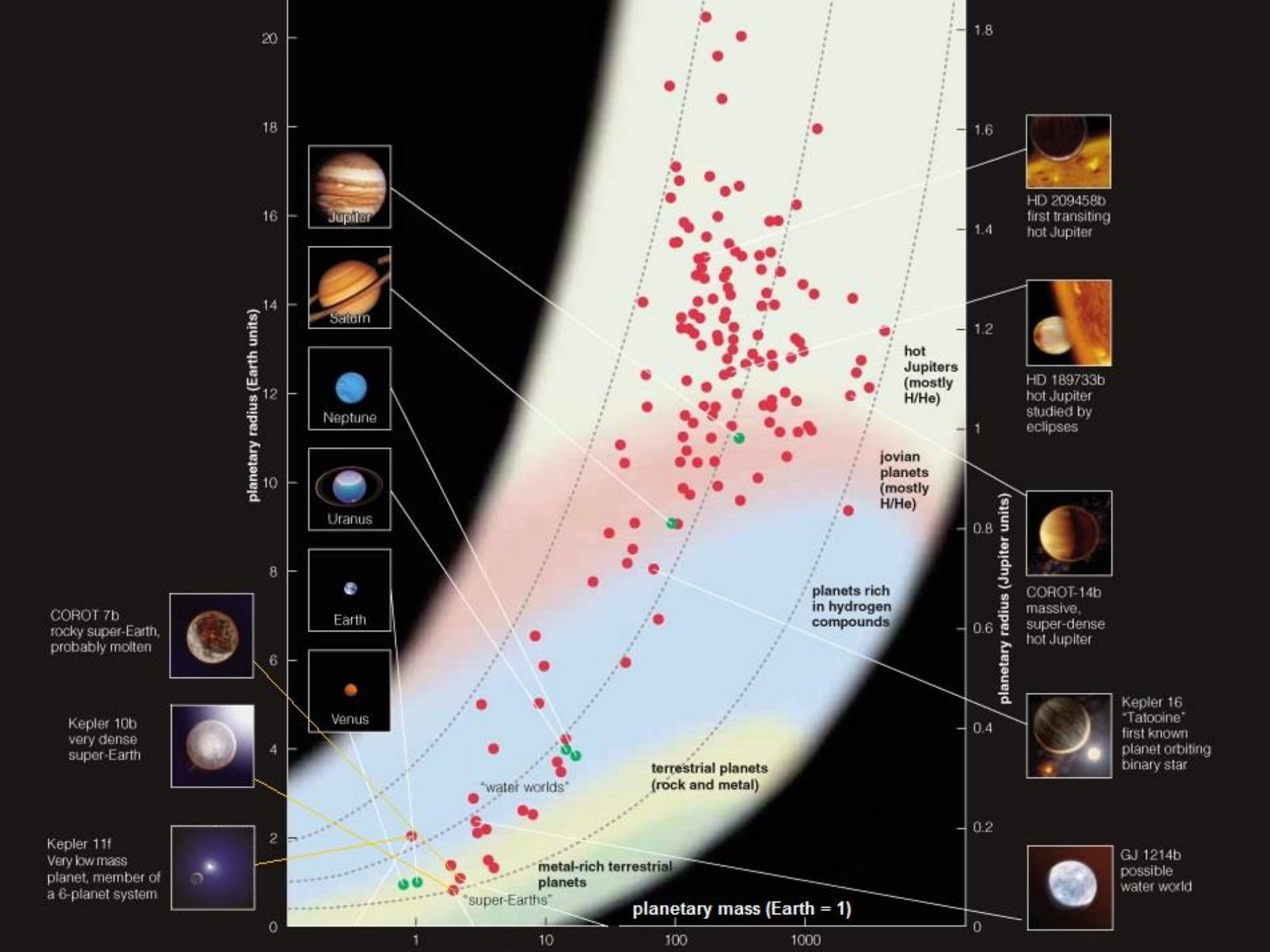
System: Kepler 10b

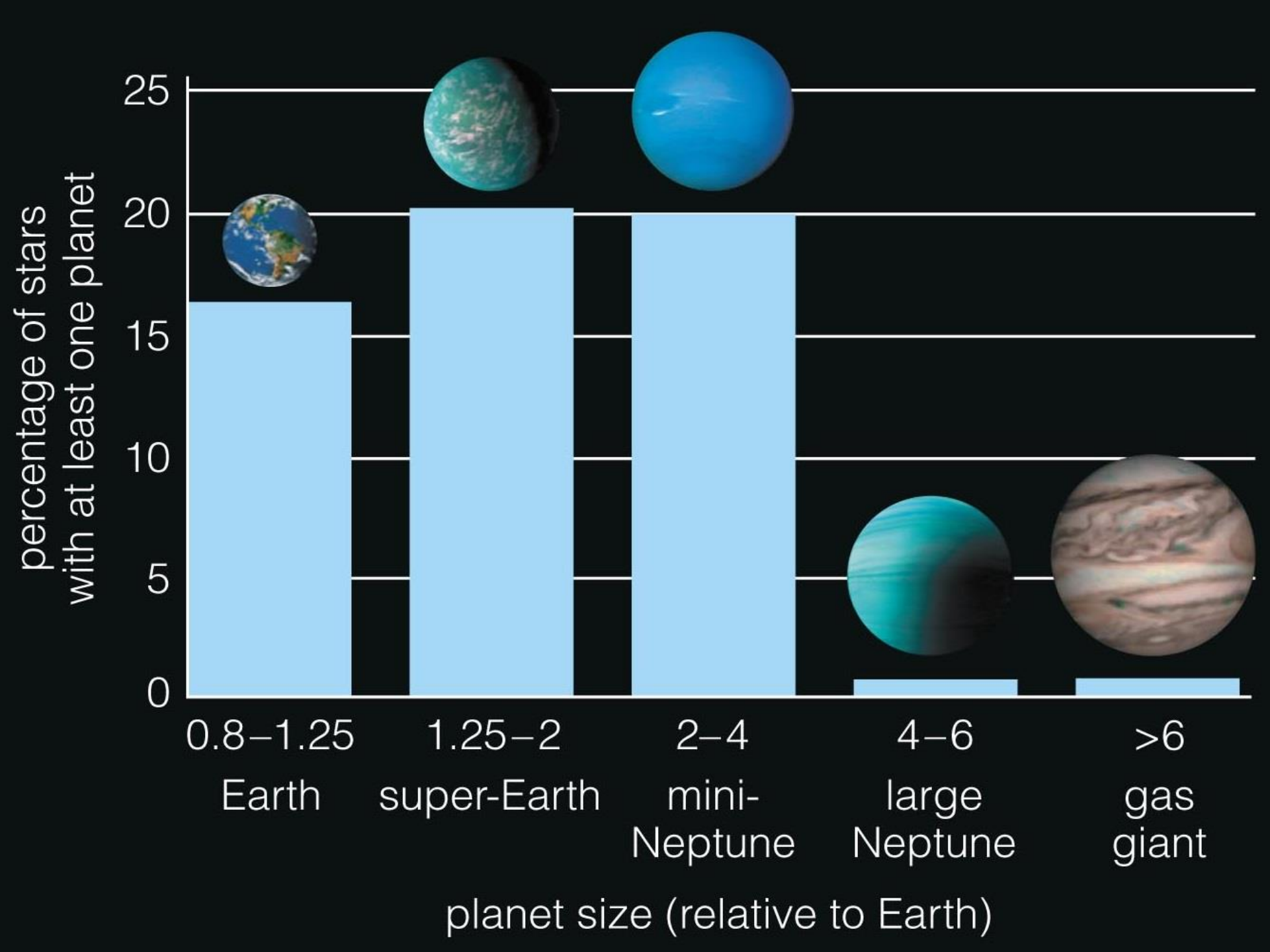
	Planetary Property	*Method(s) Used*	*Explanation*
Orbital Properties	**period**	Doppler, astrometric, or transit	We directly measure orbital period
	distance	Doppler, astrometric, or transit	We calculate orbital distance from orbital period using Newton's version of Kepler's third law
	eccentricity	Doppler or astrometric	Velocity curves and astrometric star positions reveal eccentricity
	inclination	transit or astrometric	Transits identify edge-on orbits; astrometric data measure any inclination angle
Physical Properties	**mass**	astrometric or Doppler	We calculate mass based on the amount of stellar motion caused by the planet's gravitational tug
	size (radius)	transit	We calculate size based on the amount of dip in a star's brightness during a transit
	density	transit and Doppler	We calculate density by dividing the mass by the volume (using size from transit method)
	atmospheric composition and temperature	transit or direct detection	Transits and eclipses provide data on atmospheric composition and temperature


H_2SO_4
CO_2
Venus
relative intensity
H_2O
O_3
CO_2
Earth
CO_2
Mars
0
5
10
15
20
25
30
wavelength (microns)

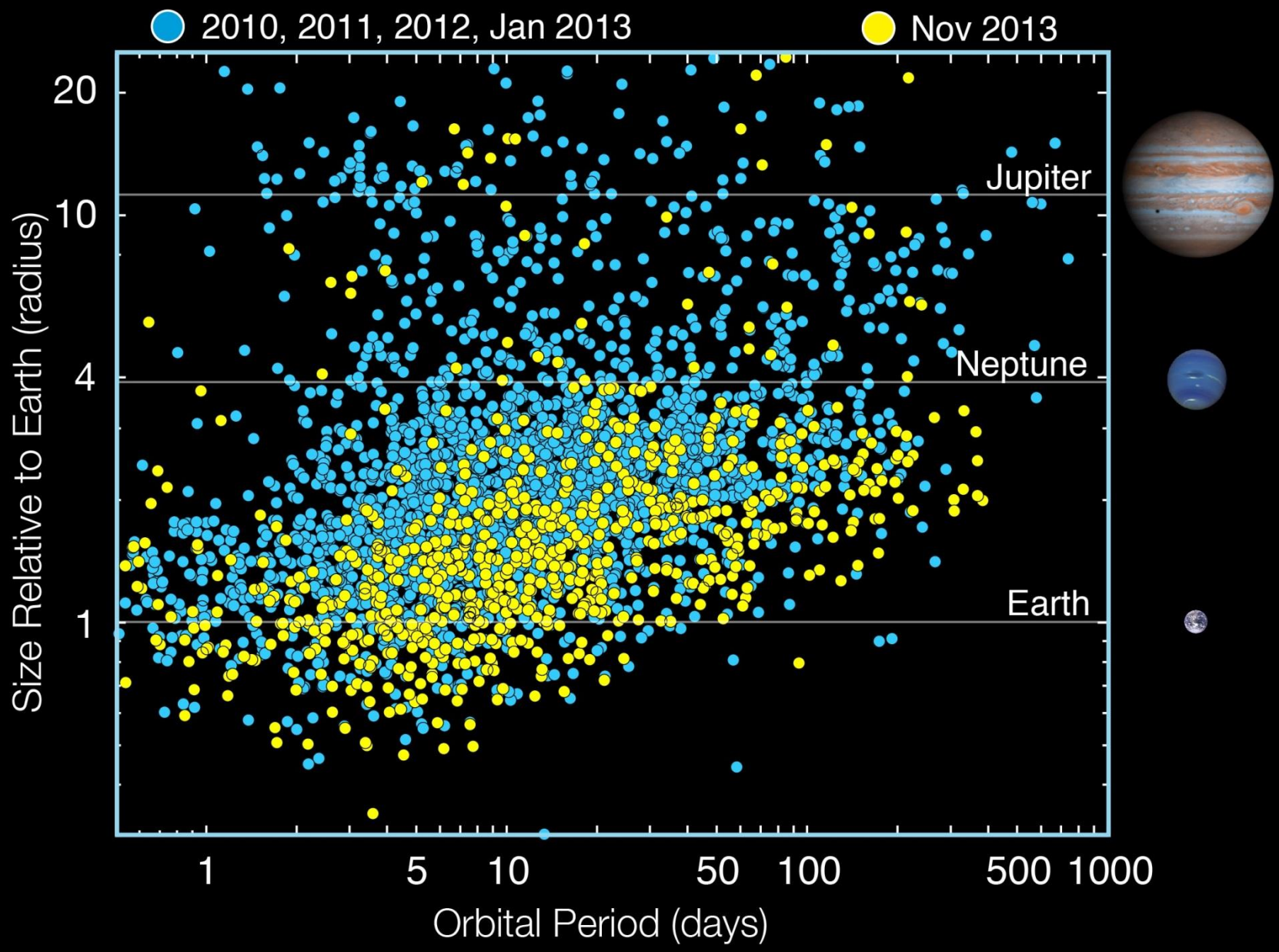
Summary of Orbital Parameters




planetary radius (Earth units)
planetary radius (Jupiter units)
planetary mass (Earth = 1)
Jupiter
Saturn
Neptune
Uranus
Earth
Venus
hot Jupiters (mostly H/He)
jovian planets (mostly H/He)
planets rich in hydrogen compounds
terrestrial planets (rock and metal)
"water worlds"
metal-rich terrestrial planets
"super-Earths"
HD 209458b first transiting hot Jupiter
HD 189733b hot Jupiter studied by eclipses
COROT-14b massive, super-dense hot Jupiter
Kepler 16 "Tatooine" first known planet orbiting binary star
GJ 1214b possible water world
COROT 7b rocky super-Earth, probably molten
Kepler 10b very dense super-Earth
Kepler 11f Very low mass planet, member of a 6-planet system


25
20
15
10
5
0
percentage of stars with at least one planet
0.8–1.25
Earth
1.25–2
super-Earth
2–4
mini-Neptune
4–6
large Neptune
>6
gas giant
planet size (relative to Earth)

Kepler Planet Candidates

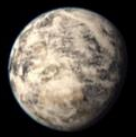



Are these planets habitable?
The fantasy part

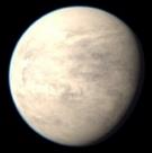
Current Potentially Habitable Exoplanets

Ranked in Order of Similarity to Earth

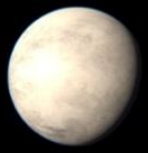
1. Gliese 667C c



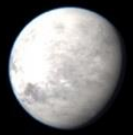
2. Kepler-62 e



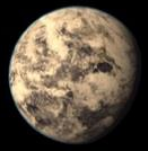
3. Kepler-283 c



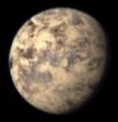
4. Kepler-296 f



5. Tau Ceti e*

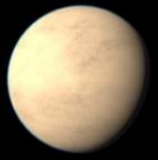


6. Gliese 180 c*

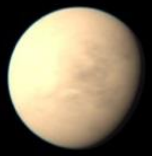


7. Gliese 667C f

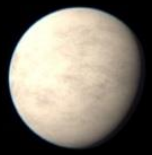
8. Gliese 581 g*



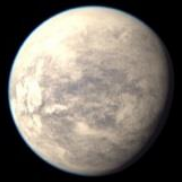
9. Gliese 180 b*



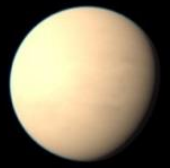
10. Gliese 163 c



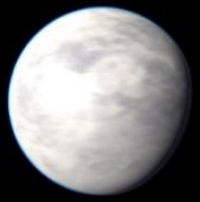
11. HD 40307 g



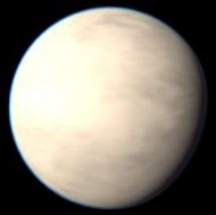
12. Kepler-61 b



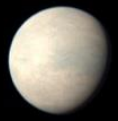
13. Gliese 422 b*



14. Kepler-22 b

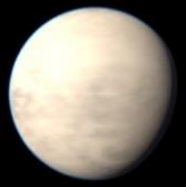


15. Kepler-298 d

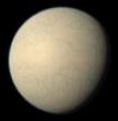


16. Kepler-62 f

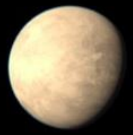
17. Kepler-186 f



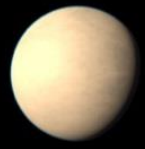
18. Kepler-174 d



19. Gliese 667C e



20. Gliese 682 b*



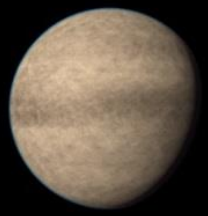
21. Gliese 581 d

*planet candidates

Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)

4 ly
Proxima b

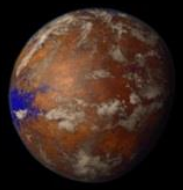


13 ly
Kapteyn b*

14 ly
Wolf 1061 c

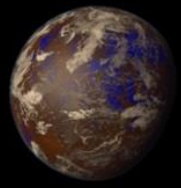
22 ly
GJ 667 C c

22 ly
GJ 667 C e*

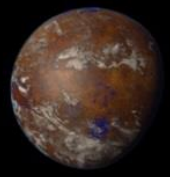


22 ly
GJ 667 C f*

561 ly
Kepler-186 f



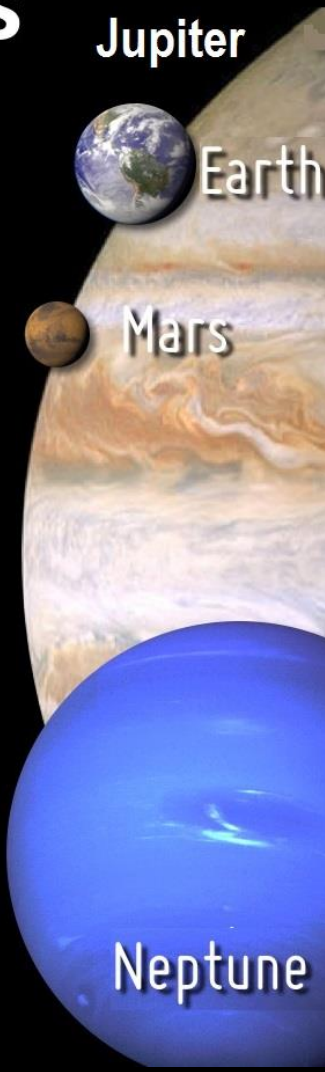
770 ly
Kepler-1229 b

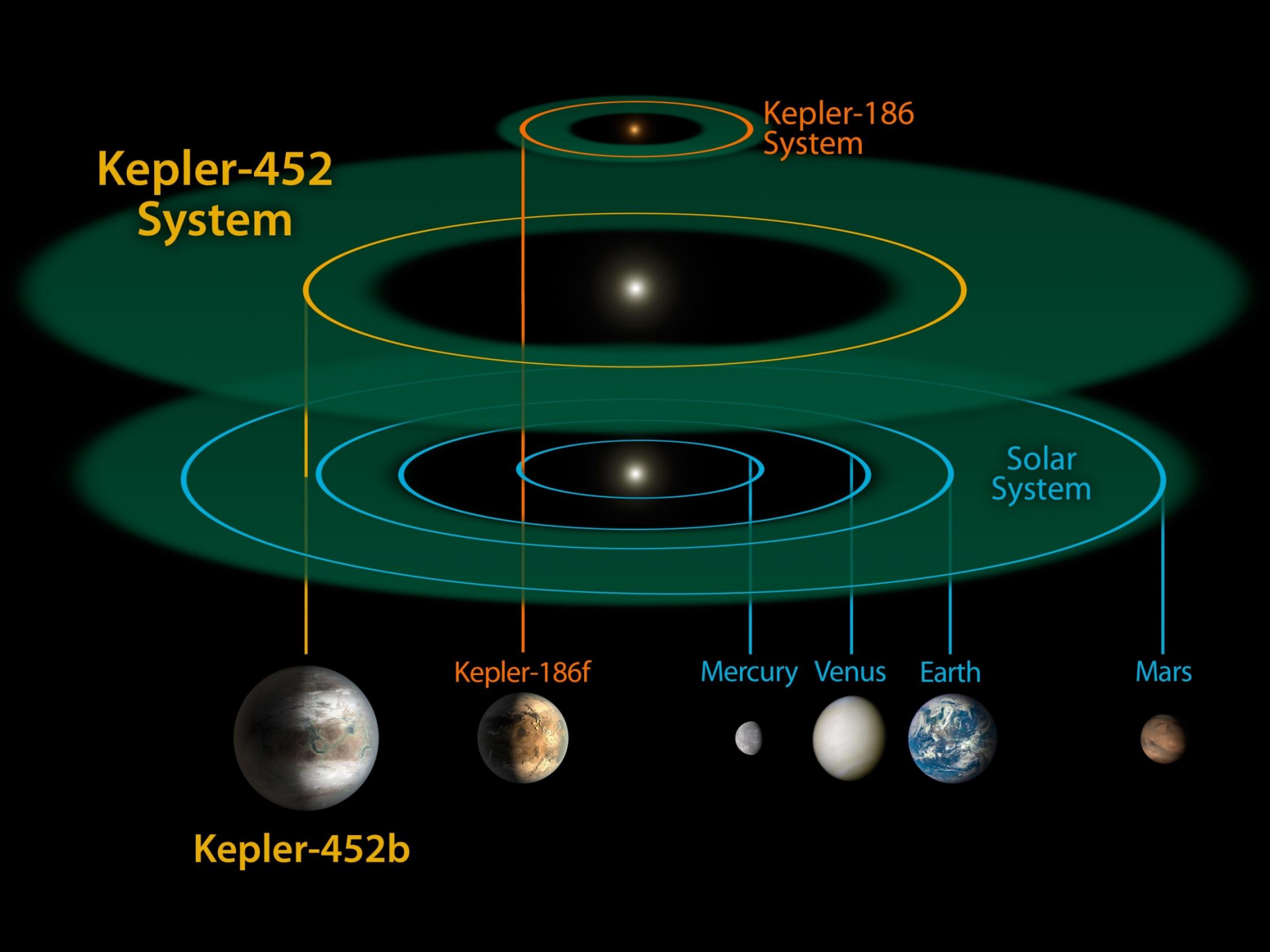


1115 ly
Kepler-442 b

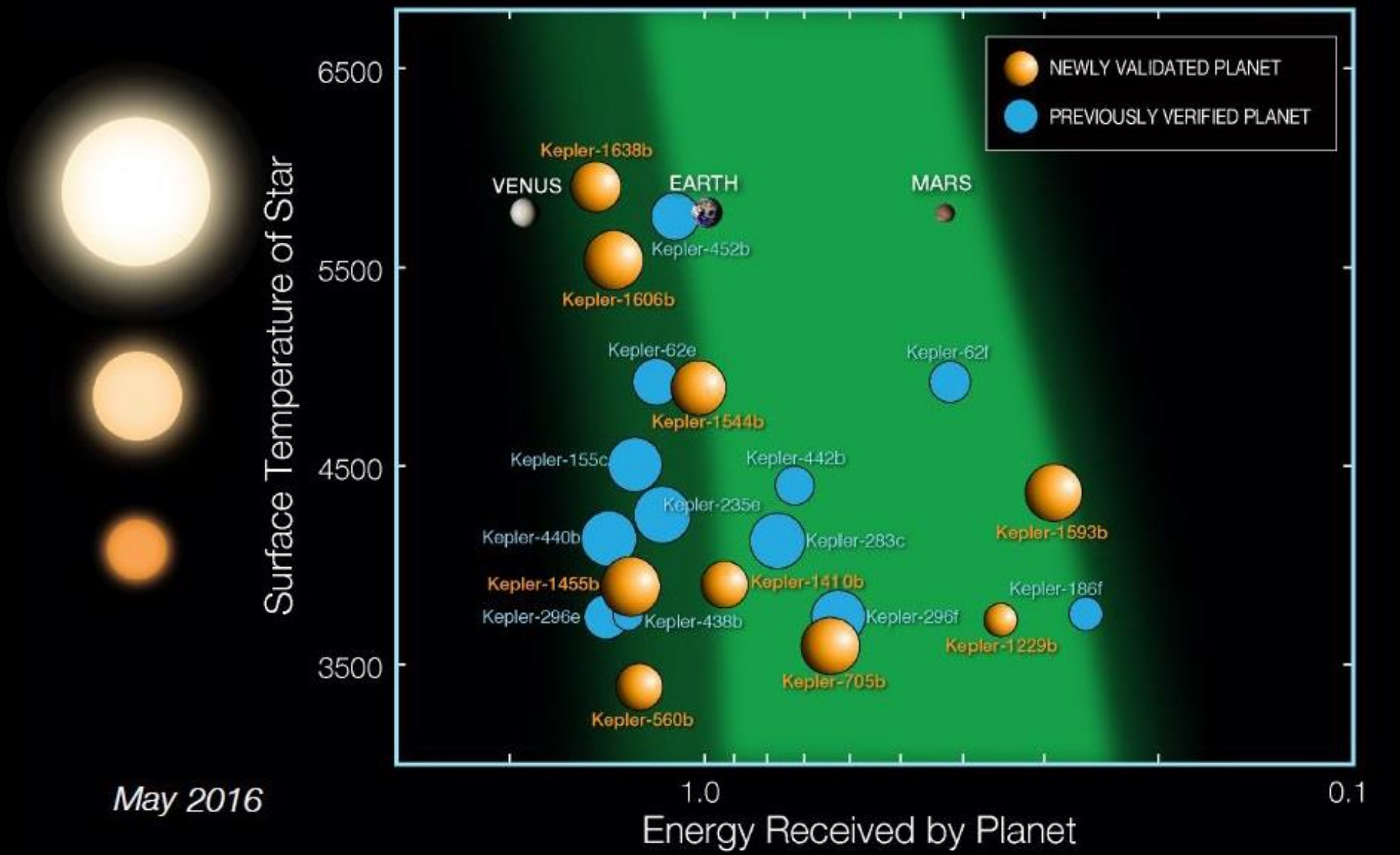
1200 ly
Kepler-62 f

Planet candidates indicated with asterisks.

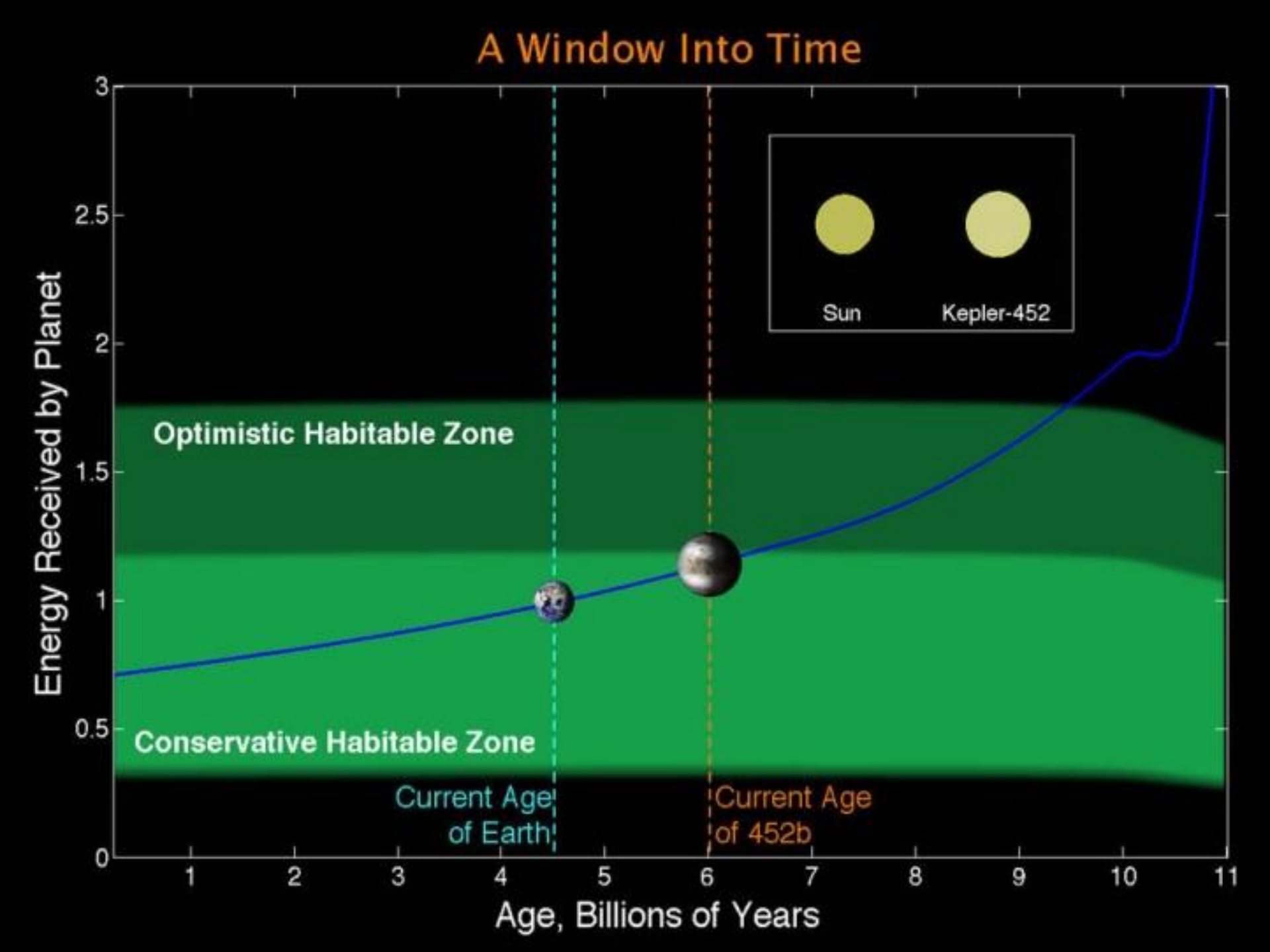



Kepler-452
System
Kepler-186
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b

Kepler's Small Habitable Zone Planets



May 2016


A Window Into Time
Energy Received by Planet
Age, Billions of Years
Optimistic Habitable Zone
Conservative Habitable Zone
Current Age of Earth
Current Age of 452b
Sun
Kepler-452
0
0.5
1
1.5
2
2.5
3
1
2
3
4
5
6
7
8
9
10
11